KEEP THE PITCHER'S ELBOW LOAD IN THE GAME

Biomechanical analysis of injury mechanisms in baseball pitching towards injury prevention

Bart van Trigt

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Keep the pitcher’s elbow load in the game

Biomechanical analysis of injury mechanisms in baseball pitching towards injury prevention

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BASEBALL PITCHING - ON THE LIMITS OF HUMAN MECHANICAL CAPACITIES

Baseball pitching is one of the fastest controlled sports movements a human can make. One of the requirements to become a professional pitcher in baseball is to throw a so-called fastball over 90mph. The fastest recorded pitch in the major league baseball is 105mph (169km/h) by Aroldis Chapman [1]. To achieve these high ball speeds, high rotational speeds and accelerations of body segments are needed, resulting in high joint loadings. These high loads at the joints can reach the strength limits of the human body. Joint loading in combination with the frequency of pitching can result in overuse injuries, especially around the elbow. Of all elbow overuse injuries, the ulnar collateral ligament (UCL) tear or rupture is one of the most common injury in professional pitchers [2]. It is evident that prevention of these (and other) injuries to occur is an important theme in baseball.

To prevent pitchers from sustaining an injury, pitches are counted in professional pitchers and pitch count guidelines are set for youth pitchers. These pitch count guidelines are a “one size fits all” principle and pitch counts in professionals provide solely information about the frequency of pitching and not about the loading of the musculoskeletal system of the individual pitcher. Recent biomechanical pitching knowledge shows the importance of including individual biomechanical information. However, it is still complex and time-consuming to quantify the musculoskeletal load during pitching in the field. However, the rise of wearable sensor technology makes it possible to measure biomechanical information in the field and to develop an “early warning system” that provides individualized feedback based on the biomechanical knowledge of the injury mechanisms.

The general aim underlying the present dissertation is to establish biomechanical injury mechanisms related to the UCL in baseball pitchers. Knowledge of these mechanisms can eventually be used to develop an ‘early warning system’ to safeguard baseball pitchers from UCL injuries.

A typical position of a baseball pitcher, with his arm in maximal shoulder external rotation. At this moment the elbow is exposed to the highest loads.

"When you stand on top of a mountain,
you can choose to stay there and enjoy the view.
But you can also climb another mountain
to see if it's beautiful on top there as well."

Nils van der Poel

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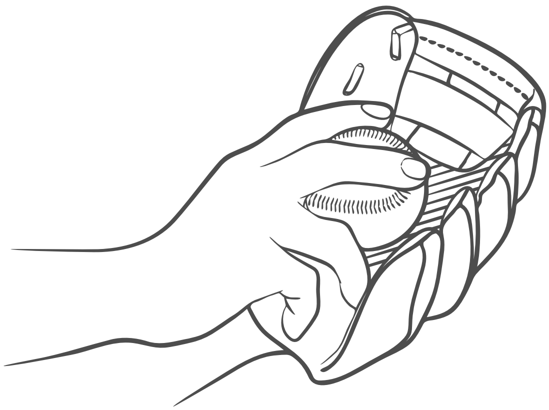

CHAPTER 1

General introduction

Waarom dit onderzoek?
Ik vertel het hier.

SOCIETAL PROBLEM

Baseball is one of the largest sports in the world. Over 500 million fans enjoy following baseball and 65 million people are participating in baseball in over 140 countries [3]. It is evident that engaging in physical activity, such as playing baseball, can have numerous benefits for physical health [4]. Playing baseball can also have positive impacts on mental health. Being part of a team provides opportunities for social connections and interaction, reduces stress and anxiety, and enhances confidence [5]. At all levels of play, baseball players and teams set goals. Recreational athletes aim to win their local competition while professional athletes aim to win the Major League Baseball (MLB) world series.

Next to these positive sides of baseball, there is another side of winning a medal: sports injuries. Baseball players are prone to (overuse) injuries. In professional baseball, the incidence of sustaining an injury is 3.61 injuries per 1000 athlete exposure hours [6]. In collegiate players, a comparable rate of 3.16 per 1000 athlete exposure hours was found [7]. Of the total number of injuries, the upper extremity accounted for 51.4%, while the lower extremity accounted for 30.6% of injuries. In addition, baseball pitchers have a 34% higher incidence rate for injuries compared to fielders. Furthermore, pitchers experience more injuries in the upper extremity [6]. The most frequent injuries in pitchers are at the shoulder and elbow. Over the last decades, the number of shoulder injuries are decreasing in professional pitchers, but the number of elbow injuries are increasing [8]. In youth and adolescent baseball pitchers, the incidence of elbow injuries is also on the rise [9].

The most common elbow injury in professional baseball pitchers is an Ulnar Collateral Ligament (UCL) rupture or tear. When the UCL is ruptured or torn, a UCL reconstruction is needed. Together with the observed increase in the incidence of elbow injuries in pitchers, there is also a substantial increase in the number of UCL reconstructions of 193% from 2002 to 2011 [10]. The high rate of UCL injuries and UCL reconstructions in baseball can have serious consequences for pitchers, and for baseball teams or clubs. For pitchers, UCL injuries can be a major setback, as they cannot play for extended periods while recovering. In addition to the physical toll of UCL injuries, they can also psychologically impact pitchers. The fear of re-injury or the inability to return to the pre-injury level can be a major source of stress and anxiety for pitchers. UCL injuries can also have a financial impact on baseball teams. Pitchers are often among the highest-paid players on a team, and an injury to a key pitcher can result in significant performance and salary losses for the team. In Major League Baseball, the largest baseball league in the world, approximately $26 million per year for each team was paid to the salary of players who could not play, due to sports injuries [11]. The financial loss after the reconstruction of a ligament in the elbow has an average of $1.9 million per baseball player. The financial loss was even higher for pitchers, on average the closing pitchers showed the highest loss of $3.9 million per pitcher [12]. The medical costs for a UCL reconstruction are $50.000 [13]. These values are negligible compared to the salary of the pitcher, and the costs of replacing a pitcher.

THE ULNAR COLLATERAL LIGAMENT

The UCL is located on the medial side of the elbow and contains different ligaments: the anterior oblique ligament, the posterior oblique ligament, and the transverse ligament. The anterior oblique ligament can be further divided into the anterior band, posterior band, and central band (Figure 1). The anterior oblique ligament connects the humerus with the ulna and originates from the humerus medial epicondyle and inserts into the ulna coronoid process. In baseball pitchers, a UCL injury occurs almost always at the anterior oblique ligament [14] and more frequently at its origin on the medial epicondyle [15]. The UCL is just like other ligaments, composed of primarily collagen fibers, but also elastin fibers, proteoglycans and other connective tissues [16]. Collagen is a strong, flexible, and elastic protein that provides structure and support. Diagnosing UCL injury involves a combination of history and physical examination and imaging tests. To physically examine UCL injuries the valgus stress test, milking manoeuvre, or moving valgus stress test can be used [17].

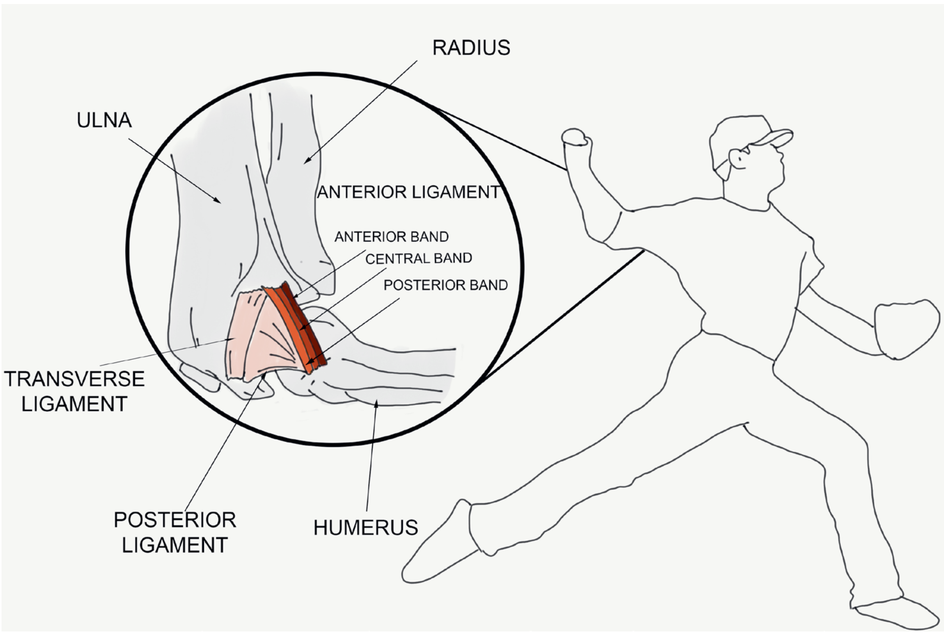

Figure 1. Schematic view of the different parts of the Ulnar Collateral Ligament in a baseball pitcher.

Ultrasound (US) and magnetic resonance imaging (MRI) are used for imaging tests [17]. The treatment of UCL injuries depends on the severity of the injury and the needs and goals of the injured person. Surgery is needed if the UCL is torn or ruptured. This involves using a graft from another tendon in the body to replace the damaged UCL either by the modified Jobe or Docking Technique [18]. This surgery is named after Tommy John, the first pitcher who underwent this surgery in 1974.

MECHANICAL FAILURE

Mechanical failure of anatomical structures can occur with a single high critical load or a repetitive submaximal load. In general, in overuse injuries, repetitive loading and cumulative activity are associated with tissue damage and loss of stiffness and strength [19]. Mechanical failure is influenced by the interaction between loading magnitude (intensity), the number of loading cycles (frequency), and loading duration [19]. The effect of the combination of loading magnitude and the number of loading cycles can be explained by a classic mechanical stress-cycle number curve (Figure 2). The curve shows the number of repetitive loading cycles that a material can sustain before complete failure. The vertical axis contains the magnitude of alternating stress (S) and the horizontal axis the number of cycles (N) to failure. All stress levels are applied at the same cyclic frequency. The curve shows a non-linear relationship between load magnitude and failure. A small reduction in magnitude results in large changes in the number of cycles to failure. For example, a reduction of 10% in the magnitude is associated with an increase of 100% in the number of cycles to failure. Mechanical failure shows the importance of load magnitude and frequency in relation to damage, of which the magnitude might be more important in relation to damage and thus injuries.

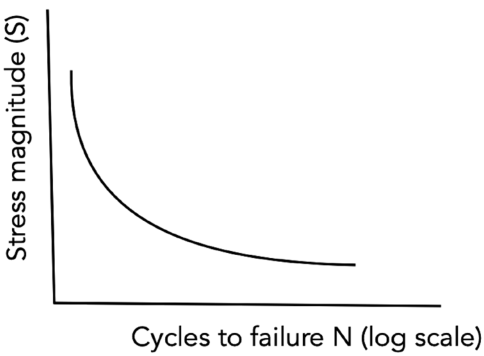

Figure 2. SN-curve of general mechanical failure of a material.

FROM MECHANICAL FAILURE TO UCL INJURIES

For the UCL, mechanical failure has been studied in human cadavers. Jordan et al. (2022) showed the nonlinear relationship between load cycling and load magnitude in relation to UCL failure [20]. However, for understanding how a UCL injury occurs, these cadaver studies seem too simplistic as they do not include adaptation. The (living) human body is a biological system and has the ability to adapt, either positively or negatively. A simple thought experiment can explain this: A mechanical failure test suggests that the UCL always ruptures after a certain number of cycles in combination with a certain load magnitude. A major league pitcher, for example, throws an average of around 100 pitches per game and plays for an average of around 15 seasons. Over the course of a career, that would add up to around 81.000 in-game pitches. This number of pitches exceeds the number of 64.949 cycles to failure in the UCL in-vitro study of Jordan et al. 2022. Thus, all pitchers should end up with a UCL tear. However, 75% of professional pitchers do not experience a UCL rupture during their careers [8]. This can be attributed to the fact that the human body is a biological system. The time between pitches, pitching sessions, and seasons, enables the ligament to recover and adapt to its environment. In understanding injuries, the mechanical model needs to be expanded with the biological aspects, including the responses and capacity of the human body. To visualize this, we used the stress-strain-capacity model of Van Mechelen et al. (1992)[21].

The stress-strain-capacity model describes how the sports environment results in (mechanical) loads on the athlete and considers the short and long term (positive and negative) responses. The model contains external exposure, internal exposure, responses, and dynamic capacity (Figure 3). Exposure can be expressed with three dimensions: intensity, frequency, and duration [22]. The main task in the sport situation of a pitcher is to outwit a batter. To fulfil this task, a pitcher performs one of the pitch types, for example, a breaking ball or fastball pitch. The pitcher's posture and movement and the exerted forces and torques depend on the pitch type and how (fast) the ball is pitched [23]. The pitch type, posture/movement, and exerted forces and torques are considered as the *external exposure*. In the context of UCL injuries, the external exposure can be expressed in an external valgus torque (intensity), pitch count (frequency), and days/months of throwing (duration). An external exposure induces an *internal exposure.* This is the stress/strain on a specific structure in the human body. In terms of UCL injuries, it is the actual mechanical load on the UCL. Internal exposure can be expressed in the magnitude of the UCL load (intensity), how many times the UCL is loaded (frequency), and how long the UCL is loaded (duration). Two biomechanical systems distinguish the boundaries between external exposure and internal exposure. Linked-segment models, which quantify posture, movement, and exerted forces and torques define the external exposure. Musculoskeletal models, which calculate muscle force and ligament load, are the system boundary of internal exposure.

As a result of the internal exposure, *responses* can be observed, which can be temporary short-term mechanical responses or long-term responses. Responses include a wide variety of levels at the whole system, cell responses, and molecular responses. Responses can either be positive or negative, i.e., the UCL can become stronger and stiffer after throwing the optimum number of balls or weaker and laxer after throwing too many or no balls at all. If the UCL will end up stronger and/or stiffer depends on both the internal exposure and its momentary capacity. This interaction between internal exposure and capacity may cause the capacity (of the UCL) to (positively or negatively) change at both the short term and the long term. If and when the UCL will rupture depends on the capacity in terms of UCL injuries, defined as the UCL strength. A UCL injury can be a short-term or long-term response. If the UCL is ruptured after a single pitch, it is a short-term response, however, it is a long-term response when the rupture occurs after throwing many balls on multiple occasions. As such, capacity is not defined as a static concept - as in the original load-capacity model - but it is considered to be dynamic [24], and because of this *dynamic capacity* occupies a prominent place in the model of Figure 3. The dynamic capacity depends on the whole physical, cognitive, and mental characteristics and capacities of the athlete, for instance, muscular strength, gender, body mass, and motivation [24]. Once a UCL injury occurs, it will negatively influence the dynamic capacity (i.e., a negative adaptation) as the pitcher is not able to pitch, which will result in a reduction of external exposure and thus internal exposure. Therefore, we call this model the stress-strain-*dynamic* capacity model. The conceptual model can be applied from different perspectives, psychophysical, physiological, epidemiological, and biomechanical. In this dissertation, the focus is on the biomechanical aspects. Understanding the biomechanics of the baseball pitch is essential, and more information about the biomechanics of the baseball pitch can be found in Box 1.

One of the processes that describes adaptation in biological tissue is super-compensation. Supercompensation is a physiological process that occurs in response to physical stress or strain, like exercise [25]. In response, the body initiates a repair process to rebuild and strengthen the damaged tissue. The tissue becomes stronger than it was before, which is known as supercompensation (Figure 4). The process of recovery takes time and is thus an important factor in supercompensation. If the next exercise is optimally timed, the body will supercompensate. However, when insufficient time is allowed for recovery, the tissue may not have fully repaired and strengthened and negative adaptation might occur (Figure 4). In addition, it becomes more complex as different tissues have different recovery times. Muscle tissue recovers faster than tendons and tendons compared to ligaments because of higher capillary density and greater protein synthesis (Figure 4). Therefore, time is an important concept in the stress-strain-dynamic capacity model.

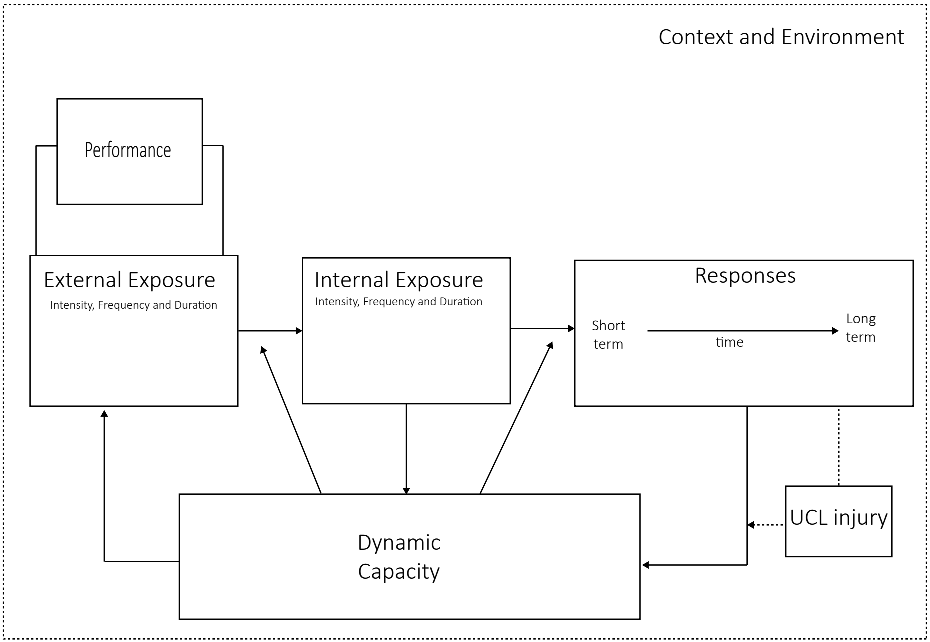

Figure 3. Conceptual stress-strain-dynamic capacity model.

POSSIBLE SOLUTIONS OF UCL INJURIES

Citius Altius Sanius research program

This dissertation is part of the research project "breaking the high load – bad coordination multiplier in overhead sports injuries" that follows from a nationwide Citius Altius Sanius (CAS) research program, with the aim to make injury-free exercise available for everyone [31]. The multidisciplinary consortium involved in the program contains data scientists, human movement scientists, and sensor system developers working within nine different projects. The CAS program is built around three fundamental projects, namely sensory technology, data science, and feedback. Six applied projects have a similar approach, combining the knowledge of these three fundamental projects. The applied projects are in each sport-related domain, covering the most occurring injuries in sports. Within this consortium, our challenge was to develop, together with the three fundamental projects, a feedback system that provides information on the (accumulated) load and key coordination parameters, based on biomechanical models and ligament loading estimates, in overhead sports, such as baseball and tennis.

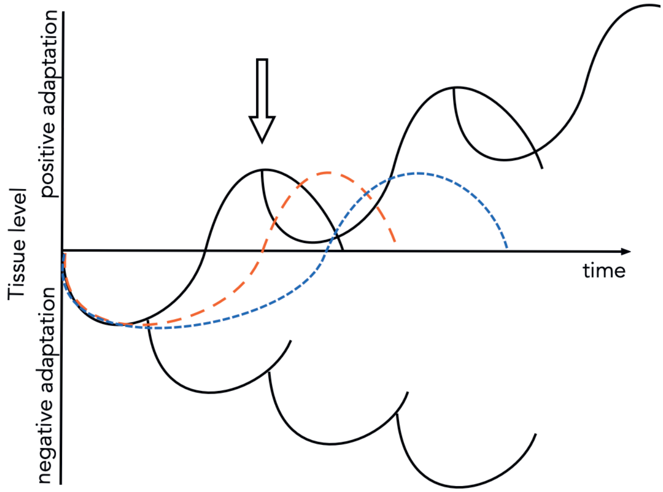

Figure 4. Simplified graph showing the effect of positive and negative adaptation according to the supercompensation process. The black line shows the effect of the adaptation of muscle tissue. After an exercise, the muscle tissue is damaged and the body starts to recover, the body super compensates when enough time is considered. When the next exercise is planned at the arrow there is optimal supercompensation for this tissue. However, when the exercise is performed too early, negative adaptation will occur. When the black line is considered muscle tissue, the tendons and ligaments can be considered as the orange and blue dashed lines, respectively. The different colored lines show the difference in recovery time between the different tissues. If the time of the next exercise is performed at the arrow, the optimal moment for muscle tissue, the blue line shows that the ligament is not recovered at that time. So, the exercise will have a negative adaptation for the ligament.

Wearable sensor technology

This dissertation is also a follow-up of project FASTBALL, a research project at the Vrije Universiteit Amsterdam and Delft University of Technology [32]. The goal of project FASTBALL was to improve the performance (e.g. ball speed) in youth baseball pitchers without increasing injury risk. In this project, a prototype wearable feedback system was developed to measure pitchers' body kinematics in the field to improve performance. The wearable sensor system contains a short and a shirt with removable sensors. As explained in Box 1, the pelvis and trunk intersegmental timing and angular velocities are important in relation to pitching performance. The sensors, which are inertial measurement units (IMUs), measure the peak angular velocity of the pelvis (short) and trunk (shirt). The timing between these peak angular velocities is the separation time. The system provides the pitcher with real-time feedback presented directly on a mobile device after each pitch on the three biomechanical variables (peak angular velocities and separation time)

1

Box 1. Biomechanics of baseball pitching

The baseball pitch is often divided into separate phases: wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow-through (see Figure 5). Pitch events characterize the changeover between each phase; maximum knee height, foot contact, maximal external rotation (MER), ball release (BR), and maximal internal rotation (MIR). These phases and events are used in biomechanics to study kinematic, kinetic, and temporal variables in relation to performance and injuries.

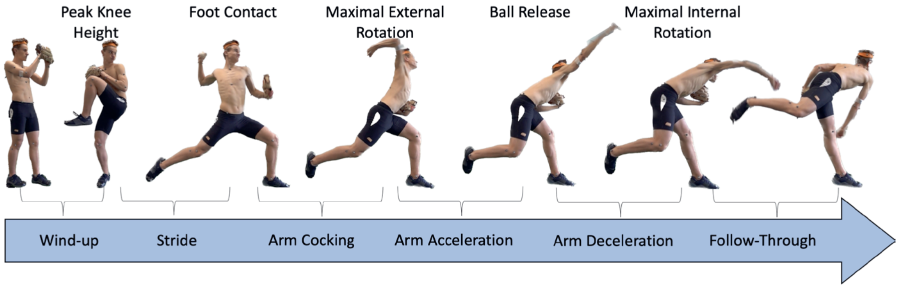

Figure 5. Shows the different events and phases of the baseball pitch.

Describing and analysing the baseball pitch in phases of joints and segments individually cannot fully explain the overhead motion, because each segment influences the other segment. Baseball pitching is a repetitive whole-body activity and requires the transfer of kinetic energy from the lower extremities through the trunk up to the upper extremities. Two biomechanical principles can explain the mechanics of baseball pitching performance, which are the summation of speed principle (also known as the "kinetic chain") and the principle of optimal coordination of partial momenta. Both principles consider the human body as a linked segment model and strive for the highest end-point velocity, but both in different ways. The partial momenta states that all segments must reach their peak angular velocity at the same time, whereas the summation of speed principles states that the subsequent distal segment peak angular velocity is initiated upon the peak angular velocity of the proximal segment. The separation time (the timing between the segment peak angular velocities) is in the partial momenta principle zero and in the summation of speed principle assumed positive with a certain optimum [26]. Thus, in overhead sports movements, the transfer of energy can be optimized by a 'correct' timing of peak angular velocities in the sequence of segmental rotations, which will – in comparison with incorrectly timed movements - result in higher ball speeds. Several studies investigated relationship between timing of pelvis and trunk rotation (peak angular velocity) in relation to ball speed [27–29].

Next to the relationship with performance, the angular velocities and intersegmental timing seem also related to joint loading. The mechanical load around the elbow is related to the time between foot contact and peak pelvis angular velocity [27] and the onset of trunk rotation [30]. Aguinaldo et al. (2019) found that the timing and mechanical power of the trunk rotation was related to the elbow load and concluded that it can be an important role in minimizing the injury risk. Thus, the influence of intersegmental timing and the angular velocities should be considered while investigating the mechanical loading around the elbow.

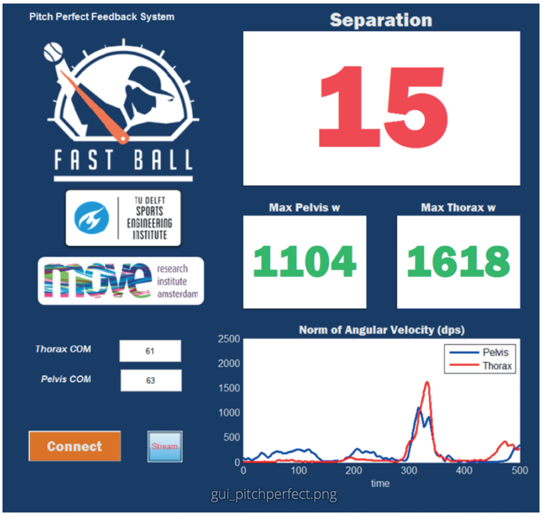

Figure 6. The interface of the PitchPerfect feedback system showing the separation time, and the angular velocities of the pelvis and trunk.

A (professional) pitcher is balancing between maximizing performance and staying healthy and injury free. The relationship between the external exposure and the performance box in the stress-strain-*dynamic* capacity model (Figure 3) shows this balance. A change in external exposure by throwing more balls (frequency) or an increase in angular velocities and accelerations (intensity) can influence performance, as more balls are pitched with higher ball speed. At the same time, an increase in external exposure probably increases internal exposure and thus injury risk.

In search of the optimal balance between performance and preventing pitchers from UCL injuries, the stress-strain-dynamic capacity model shows that it is important to investigate the relationship between external exposure, internal exposure, responses, and dynamic capacity with UCL injuries. Knowledge of these variables makes it able to develop interventions to optimize performance and prevent athletes from getting injured. This can be done in a prospective longitudinal study in which biomechanical external exposures can be related to UCL injuries. The wearable sensor system offers the solution to measure kinematics and pitch number in the field. Investigating the relationship between kinematics and pitch number with UCL injuries provides information about optimizing the external exposure in relation to the dynamic capacity of the pitcher to arrive at maximal performance with minimal injury risk.

Change of research direction because of Covid-19

The research in this dissertation was performed during the COVID-19 pandemic. The first measurements of the prospective longitudinal study were performed in March 2020, just a few days before the start of the pandemic. It was not possible to continue the prospective study during the COVID-19 pandemic due to the various challenges and disruptions caused by the virus. Prospective longitudinal studies involve collecting data from the same individuals over an extended period. However, the pandemic and the measures taken to contain it, such as lockdowns, travel restrictions, and social distancing, made it difficult or impossible to access and interact with participants. In search of the answers to prevent pitchers from UCL injuries, we shifted to experimental research. We did this by investigating relationships between and within the different levels of the stress-strain-dynamic capacity model. With the rationale that understanding possible injury mechanisms at different levels of the conceptual model is related to UCL injuries.

BIOMECHANICAL INJURY MECHANISMS

Biomechanical injury mechanisms are forces or loads causing musculoskeletal injuries. These loads are the intensity dimension of the external and internal exposure in the stress-strain-dynamic capacity model. Quantifying the elbow load during baseball pitching is complex because there is a need to measure the pitcher's movement. Biomechanical analysis makes it possible to quantify pitchers' kinematics and kinetics. In 1979, Atwater concluded that these biomechanical analyses did not yet produce sufficient data on (elbow) kinetics to explain injuries. From 1980 on, research was focused on quantifying the elbow torques and forces during pitching [33,34]. One of the torques the elbow encounters is the external valgus torque, which imparts a compressive force on the lateral side and a tensile force on the medial side of the elbow. This external valgus torque is seen as an important injury mechanism as the UCL plays an essential role in resisting this torque.

In most biomechanical research in sports, the assumption has generally been made that each measurement from one athlete is representative of all the measurements of that athlete [33,34]. While single observations and group estimates can be useful to describe a technique or indicate the load on the musculoskeletal system, it is now more widely accepted that within-pitcher variability in performance is important [35,36]. So, when pitching a baseball, all pitches look like a pitch while every pitch is also slightly different within and between pitchers. As no pitch is the same, also the elbow load will probably be different both between pitchers and within pitchers. To explain elbow injuries the devil is in the detail, only single pitches and group estimates do not quantify this detailed information. Thus, it is important to investigate the elbow load of multiple pitches of individual pitchers as this might explain why one sustains an injury and another does not.

TOWARDS PREVENTING INJURIES WITH DATA-DRIVEN SENSORS AND REAL-TIME FEEDBACK

The prevention of UCL injuries cannot be viewed in isolation. Instead, it is a component in the described “sequence of prevention” model [21]. In the “sequence of prevention” model it is shown that preventative measures should be based on the injury mechanisms [21]. Current preventative measures on pitch count solely provide information about the frequency and not about elbow loading. In addition, the guidelines for youth pitchers are a “one size fits all” principle whereas current biomechanical research shows that it is important to consider within-pitcher variability. The possible injury mechanisms which will be investigated in this dissertation could be used to develop an “early warning feedback system” to prevent pitchers from UCL injuries. This feedback system should at least monitor both the frequency (pitch number) and intensity (elbow load). Counting pitches is not that difficult, however, the latter is difficult to quantify as kinematics and kinetics are generally calculated based on measurements of posture and movement in the laboratory with optical motion capture systems. Optical motion capture systems are accurate and the gold standard, but it is complex and time consuming to use these systems in the field [37]. The wearable sensor system explained above measures kinematics and pitch number in the field. It should be investigated if it is possible to quantify the elbow load with this wearable sensor system.

PROBLEM STATEMENT

The rise of UCL injuries, the economic consequences, and the discomfort in baseball pitchers require a preventive approach to reduce injuries. Currently, the only prevention guideline is the pitch count limit for youth pitchers, while for adolescents or professional pitchers there are no guidelines. Mechanical failure and the stress-strain-dynamic capacity model show the importance of load magnitude and frequency in relation to injuries, of which the magnitude might be more important in relation to injuries. The term ‘pitch count limit’ already suggests a limit on the number of balls pitched. This prevention guideline does not include the load magnitude but solely the frequency. Furthermore, the pitch count limit is a “one size fits all” principle, but with the current biomechanical knowledge it seems important to include individual biomechanical information. Biomechanical knowledge about the UCL loading and about the individual elbow load during pitching is missing. Selecting biomechanical variables which explain possible injury mechanisms and thus UCL injuries are necessary for injury prevention. An individual instead of a “one size fits all” prevention approach also requires individual feedback. New technology and wearable sensors make it possible to develop an “early warning system” that provides individualized feedback based on the biomechanical knowledge of the injury mechanisms. However, it is still complex and time-consuming to quantify the elbow load in the field over a longer period of time.

AIM OF THE DISSERTATION

The general aim underlying the present dissertation is to establish biomechanical injury mechanisms related to the UCL in baseball pitchers. Knowledge of these mechanisms can eventually be used to develop an 'early warning system' to safeguard baseball pitchers from UCL injuries.

The sub-aims addressed in this dissertation are to:
1. Describe which risk factors are related to UCL injuries in baseball pitching, and describe the relationship between the UCL properties and elbow stabilizers with the load on the UCL during pitching (*Chapter 2*);
2. Determine whether, and if so which, elbow muscles show activity at the (assumed) critical instant of elbow load during fastball pitching (*Chapter 3*);
3. Illustrate the concept of within-individual load variability in relation to injury risk in baseball pitching (*Chapter 4*);
4. Describe the within-individual load variability of full-effort fastball pitches and determine whether the within-individual load variability can be described by a Gaussian distribution (*Chapter 5*);
5. Investigate if repetitive pitching influences the within-individual load magnitude and variability and whether repetitive baseball pitching influences the elbow muscle activation during pitching (*Chapter 6*);
6. Determine the acute UCL response to repetitive pitching, different levels of valgus stress, and elbow muscles in baseball pitchers (*Chapter 7*);
7. Predict the individual elbow load based on individual (inter)segmental rotations in fastball pitching (*Chapter 8*);

This dissertation is divided into three parts.

Part I The single pitch

The first paragraph in *Chapter 2* is a review of external risk factors related to UCL injuries. Subsequently, in *Chapter 2,* we started to investigate the relationship between UCL properties and elbow load in a single pitch. When combining the literature of in-vitro and in-vivo studies, we found a large mismatch between the UCL failure load and elbow loading during pitching. This would result in a rupture of the UCL during every single pitch. Asking ourselves the question "why do 'only' 16- 25% of the pitchers sustain an injury to the UCL?", the explanation for this mismatch is most likely the underestimation role of other elbow structures, among which are structural and functional stabilizers in inverse dynamic models. In *Chapter 3* we investigate whether the elbow muscles (functional stabilizers) are active during pitching and can shield the UCL from high loads. This could thus explain why the UCL is not ruptured during every single pitch and would be important to consider when predicting the UCL load and UCL injuries.

Part II Repetitive pitching

Part II is concerned with the effect of repetitive pitching and the question: Why does one sustain a UCL injury, and another does not? In *Chapter 4* we started to answer this question with a simple explanatory simulation injury model to illustrate the relationship between within-individual load variability and injury risk. In addition, *Chapter 2* showed that fatigue is a risk factor next to repetitive pitching. Therefore, the theoretical effect of fatigue on load variability and the injury threshold is introduced in this model. The first steps of validation of the model are performed in *Chapters 5, 6 & 7*. In *Chapter 5* we investigated whether the within-individual external valgus torque variability is present in pitchers and if it differs among pitchers. In the injury model, the UCL load is assumed to be normally distributed, and the within-individual load variability is explained with a standard deviation. Therefore, in this chapter, we also investigated if the within-individual external valgus torque showed a normal distribution. In *Chapter 6* we investigated the hypothesized effect of fatigue on load magnitude and variability in the model of *Chapter 4*. We did this by quantifying external valgus torque magnitude and variability during repetitive pitching. In this chapter, we included the information from *Part I,* about the structural and functional stabilizers which can counteract the external valgus torque. So, the effect of repetitive pitching on elbow muscle activation (functional stabilizers) was investigated. At last, in *Chapter 7*, the short-term acute response of the UCL morphology and the humeroulnar joint gap to repetitive pitching was investigated.

Part III Preventing injuries with data-driven wearable sensors and real-time feedback

This part is focused on how we can prevent pitchers from UCL injuries in the future by measuring their elbow load in the field. As shown in *Part II*, the within-individual elbow load variability seems important in relation to elbow injuries. Monitoring the within-individual elbow load variability is therefore essential. In *Chapter 8* we investigated if it is possible to predict the individual (variation in) elbow load based on individual (inter)segmental rotations of the pelvis and trunk in fastball pitching.

Epilogue

In *Chapter 9* we summarized and discussed the main findings and the conclusions of the studies in this dissertation. In addition, we point out future directions for research in injury prevention and how the biomechanical and methodological knowledge can be extended to other (overhead)sports. This chapter also reflects on the practical applications and methodological considerations.

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Ik vertel hier
over de single pitch.

PART I

The single pitch

CHAPTER 2

The Ulnar Collateral Ligament loading paradox between in-vitro and in-vivo studies on baseball Pitching

(narrative review)

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ABSTRACT

Ulnar collateral ligament (UCL) weakening or tears occur in 16% of professional baseball pitchers. To prevent players from sustaining a UCL injury, it is important to understand the relationship between the UCL properties and elbow stabilizers with the load on the UCL during pitching. In-vitro studies showed that an ultimate external valgus torque of 34 Nm would rupture the UCL, which is in apparent conflict with the reported peak valgus torques in pitching (40-120 Nm). Assuming both observations are correct, the question rises why ‘only’ 16 out of 100 professional baseball pitchers sustain a UCL rupture. Underestimation of the effect of other structures in in-vivo studies is most likely the explanation of this mismatch, because the calculated in-vivo torque also includes possible contributions of functional and structural stabilizers. In-vitro studies show that the flexor-pronator mass has the potential to counteract external valgus torque directly, whereas the elbow flexor-extensor muscles combined with the humeroradial joint might have an indirect effect on valgus torque by increasing the joint compression force. Accurate experimental electromyography data and a more detailed (musculoskeletal)mechanical model of the elbow are needed to investigate if and to what extent the structural and functional stabilizers can shield the UCL during pitching.

INTRODUCTION

Baseball pitching is a highly dynamic movement that shows high injury rates. Conte et al. (2001) reported that 48% of the injured players in Major League Baseball (MLB) were pitchers. The shoulder and elbow were found to be the most frequent injury sites, responsible for 29% and 22% of the disabled days, respectively. A study by Lyman et al. (2001) on 298 youth pitchers reported that over two seasons, 26% of the pitchers experienced elbow pain. In 68% of those, elbow pain was experienced on the medial side. Most of the time, this pain is related to ulnar collateral ligament (UCL) injuries. Overall, the prevalence of UCL reconstruction is 16% in professional baseball pitchers [3].

The elbow is usually described as a hinge joint, allowing flexion-extension. This hinge-like behaviour is because rotations in other directions, such as varus-valgus, are resisted by structures around the joint, with the joint shape, joint ligaments, and joint-crossing muscles as the most important factors [4].

The late cocking phase and acceleration phase of the pitching movement have been reported to be critical in terms of elbow load [5]. The elbow load in these phases is also high in other overhead sport motions, like the tennis serve [6]. In these phases, the elbow encounters an external valgus torque, which imparts a compressive force on the lateral side and a tensile force on the medial side of the elbow. The UCL plays an essential role in resisting this external valgus torque.

Knowledge about UCL loading may be used to prevent overuse UCL injuries. In-vitro studies investigated the role of the UCL and its different parts in resisting external valgus torque. These static in-vitro studies provide more insight into the function, biomechanical properties, and the ultimate torque of the UCL ligament, but do not provide information about the UCL loading during the baseball pitch or other overhead sports motions. It is highly complex, if not impossible, to measure the direct load of the UCL during pitching in a non-invasive way. To our knowledge no experimental study has been published which directly measured UCL load. The closest to this have been inverse dynamic studies that quantified the external valgus torque around the elbow as an indication for UCL loading. Most likely, other structures around the elbow are also likely to resist the external valgus torque [4] although more insight about contribution of these structures is needed to understand UCL injury risk.

The goal of this review is to provide an overview of what risk factors are related to UCL injuries, and to better understand the relationship between the UCL properties and elbow stabilizers with the load on the UCL during pitching, by combining literature of in-vitro and in-vivo studies.

Risk factors of UCL injury in pitching

It is widely accepted that elbow injury results from overuse. High torques and forces in the joint stress the ligaments, and repetitive valgus overload from throwing may cause a micro rupture. When overuse is sustained, and the body is unable to compensate, this can lead to attenuation or even tear of the UCL [5,7–10]. Many epidemiological studies have looked into factors that influence elbow injury risk in pitching (Table 1) [2,11–14].

Pitching with self-reported fatigue showed increased odds of elbow pain [2]. Olsen et al. (2006) reported that pitchers who underwent elbow surgery were more likely to experience arm pain or fatigue during pitching.

The number of pitches thrown per inning, game, and season is frequently associated with higher injury risk. Olsen et al. (2006) showed that injured pitchers, before sustaining an injury, threw more months per year (8 versus 5), games per year (29 versus 19), innings per game (6 versus 4), pitches per game (88 versus 66) and pitches per year (2500 versus 1300) compared to the uninjured matched control group. Fleisig et al. (2011) found that pitchers who threw more than 100 innings a year were 3.5 times more likely to sustain an injury. In youth pitchers it has been shown that throwing more than 600 pitches per season during games increased the odds of developing elbow pain by 3.4 times compared to throwing fewer than 600 pitches [2].

Not surprisingly, as ball speed is by definition related to external load on segments, three studies found that ball speed is related to injury risk. The case-control study by Olsen et al. (2006) found a difference between injured and non-injured pitchers (88 versus 83 mph), as did Bushnell et al. (2010) (89 versus 85 mph). Next to adult pitchers, also youth pitchers show an association between ball speed and elbow pain [15]. Ball speed did not decline following return to sport: Keller et al. (2016) compared ball speed of MLB pitchers before and after UCL reconstruction surgery with data from a matched control group with no injury history. No significant difference in ball speed between groups was found.

Pitch type percentage (fastball, curveball, slider etc.) is another risk factor that has been investigated in relation with injuries. Keller et al. (2016) reported that throwing more than 48% fastballs increased the UCL injury risk in professional players. In contrast, this was not supported by the study by Olsen et al. (2006) in which both control and injured college pitchers threw 61% fastballs. The absence of a correlation between percentage of fastballs and injury risk in Olsen's study might be explained by the fact that the players were younger and that at lower level overall more fastballs are thrown (Table 1).

Body weight has been reported to increase injury risk by both Olsen et al. (2006) and Lyman et al. (2001). However, these studies do not agree on the influence of pitcher height: Olsen et al. (2006) found that an increased body height corresponded with higher injury risk, while Lyman et al. (2001) found that decreased height was a risk factor for injury. Theoretically,

Table 1. An overview of five epidemiological studies predicting elbow pain, injury or surgery. Descriptive information of the different studies is provided about, subjects, age, pitchers level, highest fastball speed, study design, data collection and statistical tests. The included predictors are: fatigue, pitch count, ball speed, pitch type percentage, body weight and body height. The table shows whether a positive (+), negative (−) or no significant (0) relationship between the predictor and higher pain/injury risk was found, with its corresponding odds ratio (OR). a OR for > 600 compared to < 300 pitches. b OR increased with a higher weight class. c OR decreased with greater height class. ± = standard deviation.

Study design	Lyman (2001)	Fleisig (2011)	Olsen (2006)	Keller (2016)	Bushnell (2010)
Subjects	298 pitchers	481 pitchers	95 injured pitchers 45 control pitchers	83 injured pitchers 83 matched control	9 injured 14 control pitchers
Age (range)	10.8 ± 1.2 (8-12)	12.0 ± 1.7	18.5 ± 1.5	28 ± 4.2	28 (20-30)
Pitchers level			high school/college	professional, MLB	professional
Fastball speed (injured vs control)			88.3 vs 82.7 mph	91.3 vs 91.5 mph	89.22 vs 85.22 mph
Data collection	2 season follow-up interviews after game and season	10-year follow-up Annual interview	1-year time period retrospective survey	2 years before and after surgery online data	3 seasons cohort study online data and disabled list
Predicting	elbow pain	elbow injury	elbow surgery	UCL reconstruction	elbow injury
Statistical outcome	odds ratio	odds ratio	t-test	t-test	t-test
Predictor					
Fatigue	+ (OR 5.94)		+		
Pitch count	+ pitches/year (OR 3.44/0.47[a])	+ innings/year (OR 3.5)	+ months/year + games/year + innings/game + pitches/game + pitches/year		
Ball speed			+	0	+
Pitch type percentage			0	+	
Body weight	+ (OR 1.31-5.39[b])		+		0
Body height	− (OR 0.79-0.35[c])		+		0

greater body height and weight would both increase the inertia of the forearm, leading to higher torques around the elbow. However, the stabilizing structures, as muscles, around the elbow might also be stronger in heavier or taller players. Therefore, body fat percentage might be an interesting risk factor to investigate in relation to elbow injuries.

Strength training is also an important aspect in pitching. Strength training might influence injury risk, since weight lifting during the season was found to increase the risk of elbow and shoulder pain in 8-12 years old pitchers [2]. However, this weight lifting was self-reported, which makes it unclear how the training was performed and whether it was conducted under supervision. In contrast, Sakata et al. (2017) [16] found that medial elbow injuries in youth baseball pitchers were significant lower in their intervention group. This intervention was more sports specific, with nine strength- and stretch exercises, compared to Lyman et al. 2001. It seems that strength training programs should focus on motor control to prevent elbow injuries. The effect of strength training in adults has not been investigated

Lastly, it has been widely suggested that an “improper” pitching technique can increase injury risk [5,10,17]. Pitching technique can cause higher joint torques and forces. If knowledge is gained on what pitching technique leads to higher injury risk (what “improper” pitching technique is), pitchers can adjust their technique in order to prevent injury.

Overall, fatigue and pitch count seem to be related to UCL injuries. The literature is not consistent about the relation between body weight and height, ball speed and pitch type percentage in relation to UCL injuries. To understand the risk factors in relation with possible injury mechanisms it is necessary to understand the behaviour of the UCL and other joint stabilizers during pitching.

THE DIFFERENCE IN UCL AND ELBOW LOAD BETWEEN IN-VITRO AND IN-VIVO STUDIES

UCL load in in-vitro studies

In-vitro studies showed that the UCL complex consists of three different ligaments: the anterior oblique ligament (AOL), the posterior oblique ligament (POL), and the transverse ligament (TL). Some studies refer to bundles instead of ligaments (Figure 1). According to Kaufmann et al. (2019), the primary stabilizer in resisting external valgus torque is the AOL, whereas the contribution of the POL is negligible, and the TL lacks the ability to resist valgus torque due to its origin and insertion on only the ulna [18]. The AOL can be further divided in the anterior band and the posterior band [19,20], and one study even refers to a third central band [21] (Figure 1).

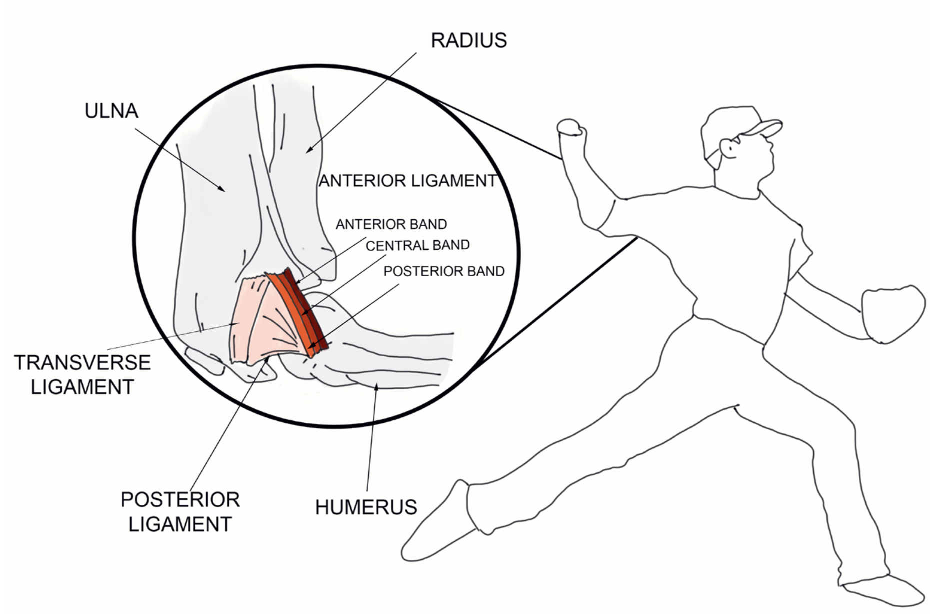

Figure 1. Anatomical sketch of the UCL during pitching. The UCL consists of the transverse ligament, posterior oblique ligament and anterior oblique ligament. The anterior oblique ligament contains three parts; the anterior, posterior and central band.

Several studies investigated the mechanical properties of the AOL in-vitro, see Table 2 [22–26]. All studies showed an ultimate torque resistance strength of approximately 30 Nm. Ahmad et al. (2003) and McGraw et al. (2013) pre-loaded the cadavers to 1 Nm and then loaded them to failure. Both studies also calculated the stiffness: Ahmad et al. (2003) found a mean stiffness of 42.81 N/mm and McGraw et al. (2013) a mean stiffness of 21.0 N/mm. This substantial disparity might be explained by different elbow flexion angles (70 and 30 degrees), different loading rates (50% strain/s and 67% strain/s) and the properties of the cadavers (male versus both sexes, mean ages 44 versus 52 years). Another study [26] estimated the UCL ultimate force by dividing the applied ultimate failure torque by an estimated moment arm. This approach has a drawback that the moment arm is actually unknown and might be influenced by testing conditions. Therefore, directly calculating the ultimate force of a ligament will provide more precise information about its mechanical properties. Regan et al. (1991) investigated UCL strength by preparing bone-ligament-bone samples, which were preloaded and then loaded to failure with a loading rate of 100% of the initial length per second. They determined a failure load of 260.9 N and stiffness of 1528 N for the AOL. Comparable values were found by Jackson et al. (2016), who found a failure load of 293.1 N for the AOL and a mean yield point of 203.3 N.

Table 2. Mechanical properties of the UCL in different in-vitro studies.

	Number of specimens (m=male, f=female)	Age (years)	Ultimate valgus torque (Nm)	Stiffness (N/mm)	Failure load (N)	Elbow Flexion Angle (degrees)
Ahmad et al. (2003)	10 (10 m)	43 (26-60)	34.0 ± 6.9	42.81 ± 11.6	N/A	70
McGraw et al. (2013)	10 (3 f & 7 m)	52 ± 6	35.0 ± 14.0	21.0 ± 9.0	N/A	30
Hechtman et al. (1998)	31 (N/A)	N/A	22.7 ± 9.0	N/A	N/A	45 or 30
Regan et al. (1991)	8 (6 f & 2 m)	N/A	N/A	N/A	260.9± 71.3(AOL) 158.9 ±4 0.1(POL)	N/A
Dillman et al. (1991)	11	N/A	32.9 ± 5.4	N/A	642 ± 5.4	N/A
Jackson et al. (2016)	6 (1 f & 5m)	67 (50-83)	N/A	N/A	293.1 ± 38.7(AOL)	70

The contribution of the anterior and posterior band of the AOL to resist an external valgus torque varies with elbow flexion. Two studies reported that only the anterior band stabilized the elbow in varus-valgus motion over the full range of flexion, whereas the posterior band was a secondary constraint from 90 degrees [19,27]. More recent studies found that the anterior band showed a constant strain pattern over the elbow flexion-extension range, whereas the strain in the posterior band increased linearly with elbow flexion [20,21]. In addition, Jackson et al. (2016) found that both bands showed similar intrinsic properties, which indicates the importance of the insertion point and not the intrinsic differences between the anterior and posterior band [20]. Overall, elbow flexion influences how the AOL is loaded. The anterior band of the AOL is important in stabilizing over the full range of flexion, whereas the posterior band seems to have a more stabilizing effect in a flexed elbow.

In all of the studies mentioned earlier, only the study of Jackson et al. (2016) took material fatigue into account. Most measurement protocols started with a pre-load and increased the load until failure. However, as mentioned before, most of the UCL injuries are overuse injuries and related to fatigue and pitch count. Therefore, it would be useful to take material fatigue of the UCL into account.

The association between external valgus torque and UCL injuries during pitching

Most research in the field of baseball pitching biomechanics has focused on quantifying kinematic and kinetic parameters across the movement. Net joint torques between segments are calculated by inverse dynamics. In multiple studies, across various levels of pitching and ages of the pitcher, the peak external valgus torque has been reported in the range of 45-120

Nm during the late cocking or acceleration phase in the baseball pitch [28–30]. It has been shown that the peak external valgus torque is lower in youth baseball players (range of 18-27Nm) [31,32], probably because of lower ball speed, body weight and height.

Some studies investigated the effect of the external valgus torque in relation with UCL properties. While it is generally assumed that a high external valgus torque around the elbow joint places the UCL under high stress leading to an increased UCL injury risk, only a few studies provide (indirect) support for this assumption. Hurd et al. (2011) found a weak but significant relationship between external valgus torque and UCL thickening ($r = 0.45$ and $P = 0.02$). Anz et al. (2010) first measured and then subsequently followed 23 professional pitchers for three seasons. The results showed that those pitchers that got injured within the three-season window threw with a significantly higher external valgus torque compared to the non-injured group prior to the follow-up period. [34]. Although these studies investigated the link between external valgus torque and UCL injury and properties, they do not provide information about the UCL loading during a baseball pitch.

The apparent mismatch between load in in-vitro studies and pitch dynamics

Assuming that both in-vitro studies and in-vivo studies are inherently valid, it can be concluded that there is a mismatch between the ultimate in-vitro valgus torque (34Nm) and in-vivo peak valgus torque in adolescents (45-120Nm). If we combine these data, the peak torque in a pitch exceeds the ultimate valgus torque of the UCL by 10-95Nm. This means that during almost every pitch the valgus torque of the UCL is exceeded, which raises the question why 'only' 16 out of 100 elite baseball pitchers sustain a UCL rupture during their career.

There are three not mutually exclusive possibilities that contribute to this paradox, namely: underestimation of the in-vitro ultimate valgus torque; overestimation of the in-vivo peak valgus torque; or underestimation of the influence of other torque-resisting structures.

Possibly the in-vitro ultimate valgus torque is underestimated due to the fact that these studies are done in adult specimens with likely no background in baseball or overhead sports. As a consequence of pitching the UCL will adapt and thus will be able to resist more loading. On the other hand, and working against the underestimation argument, UCL in-vitro studies have not investigated material fatigue where it is known from the work by Thornton et al. (2015) on rabbits that the knee medial collateral ligament ruptures earlier by fatigue and creep [35].

Overestimation of the peak external valgus torque in-vivo could be due to the assumptions made in inverse dynamic models used, like anthropometric models, coordinate systems and joint centres [36]. For example, most inverse dynamics models define the midpoint between the medial and the lateral humerus epicondyle as the joint rotation centre. Moving the centre to medial or lateral would change the magnitude of the calculated torque. It is, however, mathematically unlikely that this will lead to torque values that are lower than the in-vitro estimate ultimate torques. These model assumptions could also explain the large differences between peak external valgus torques in different inverse dynamic studies (45-120Nm). If we assume that the study with the lowest external peak valgus torque of 45 Nm in adult pitchers is the 'true' value, there is still 10 Nm difference compared to in-vitro studies.

The third option, underestimation of the effect of other structures in-vivo is most likely the explanation for the difference between in-vivo and in-vitro data. The in-vivo torque is calculated as resultant joint torque, which also includes the possible contributions of muscles and joint articulations and should thus in fact not be solely attributed to the UCL. To really quantify the UCL injury risk these factors should be considered.

STRUCTURAL AND FUNCTIONAL ELBOW STABILIZERS

Structural stabilizers

When an elbow resists valgus torque, a compression force on the lateral side, between the radial head and the humerus occurs. In mechanical terms a compression force provides stability. So, the geometry of the radiohumeral articulation could be related to resist the valgus torque over the full range of motion. Hotchkiss & Weiland (1987) placed thirty elbow cadavers under a valgus torque of 1.3 Nm over 2 seconds. They found that the torque-displacement curve increased by an average of 30% at 0°, 45° and 90° elbow flexion, after excision of the radial head. It is important to note that in their study cutting the UCL resulted in such destabilization of the joint that the torque-displacement curve could not be measured. Morrey et al. (1991) performed comparable tests, with only gravity as applied torque, and found that when the UCL was intact sectioning the radial head did not result in any change in laxity at all. When the UCL was cut, it did result in up to 12.5° more laxity, pointing to the radiohumeral joint as a secondary stabilizer. An important difference compared to the study of Hotchkiss & Weiland (1987) is that their experimental setup contained three upper arm muscles (biceps, brachialis and triceps), which could increase the compression force and thus stability when the UCL was cut. Another difference between the two studies is that Morrey et al. (1991) only applied a gravitational torque, it might be possible if a dynamic torque was applied, also a laxity was found with an intact UCL. It should be noted that in both studies the applied torque is very low compared to the inverse dynamic valgus torques.

In conclusion, the UCL is important in stabilizing, but next to the UCL also the radiohumeral joint is a structural stabilizer that can resist elbow valgus torque. It seems that the magnitude of contribution depends on the amount of compression force and the magnitude of the externally applied torque.

Functional stabilizers

Muscles have the potential to function as functional stabilizers in counteracting an external valgus torque. Davidson et al. (1995) started investigating the anatomy of the Flexor Pronator Mass (FPM) muscles, which consist of the flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS), flexor carpi radialis (FCR), and pronator teres (PT), to identify which muscles lay directly over the UCL in 30, 90 and 120°of elbow flexion. They found that the FDS and the FCU partially or fully lay over the UCL, whereas the FCR and PT never lay over the UCL. Their conclusion was that the FCU is optimally positioned to provide support to the UCL, although the FDS has a greater size and force potential for valgus stabilization [39]. Multiple studies tried to quantify the contributions of these various muscles in elbow stability in cadavers, by different methods with loading and unloading muscles and with intact and released UCL and at different elbow flexion angles (Table 3). The release of FPM muscles tension with a released UCL showed an increased valgus angle only with the forearm in supination [40]. Several studies investigated the effect of the individual FPM muscles in a neutral forearm position [41–43]. Park and Ahmad (2004) simulated the muscle loads with nylon cords at 15N by a released UCL, it was shown that the FCU had the most substantial contribution, followed by the FDS and FCR and the PT has the smallest contribution. Lin et al. (2007) shares this conclusion, instead of cutting the UCL, they measured the strain of the UCL when loading the different FPM muscles. They found a decreased strain on the UCL. In contrast to these two studies, Udall et al. (2009) adjusted the loading on the individual muscles to its cross-sectional area and concluded the FDS to be the most significant contributor to valgus stability, followed by a similar contribution of the FCU and the PT (Table 3).

Fewer studies discuss the contribution of upper arm muscles in valgus stability. Morrey et al. (1991) showed that simulated functional muscle contributions from the biceps, brachialis, and triceps reduce the valgus-angle. Similarly, Seiber et al. (2009) simulated these muscle contributions with nylon lines attached to the tendons near the insertion of these muscles. A load of 20 N was applied to the triceps nylon line and 10 N each to the biceps and brachialis nylon lines. The release of these muscles resulted in an increased valgus-angle. This result could be explained by the effect of the compression force on valgus stability. Due to the co-contraction of the flexor and extensor muscles, a compression force in the elbow is present, but these muscles cannot provide compression force when they are inactive. Next to the upper arm muscles, also the forearm muscles might have an indirect effect due to co-contraction like the extensor supinator mass in relation to the FPM. Hence, the triceps, biceps, brachialis, anconeus, and extensor pronator mass muscles cannot provide direct valgus stability, but could possibly have an indirect effect by providing a compression force in interaction with the joint articulation (Figure 2).

*Table 3. In-vitro studies that investigated the effect of muscles on resisting external valgus torque. * indicate that the muscle has the potential to resist external valgus torque.*

	Investigated muscles	**Forearm position**	**Elbow flexion angles**	**Method**	**Outcome variable**
Seiber et al. (2009)	FPM*	Pronation, Supination*, Neutral	30 50 70	Elbow loaded with 2 Nm valgus torque and simulated biceps, brachialis, and triceps. The passive FPM loading was then released by cutting the tendons.	Valgus angle
Lin et al. (2007)	FCU* FDS* FCR* PT	Neutral	45 90	Muscles were loaded with a free weight pulled a wire that was sutured onto the respective muscles and was loaded individually in degrees by 10 N.	Strain relieve in the UCL (%/10N)
Park & Ahmed (2004)	FCU* FDS* FCR* PT*	Neutral	30 90	The FPM muscles were individually loaded with a released UCL, and all loaded equally with 15 N. The triceps, biceps, and brachialis were loaded by simulated free weights pulling cords.	Valgus angle
Udall et al. (2009)	FDS* FCU* PT*	Neutral	30 60 90	The FDS, FCU, and PT muscles were adjusted to its cross-sectional area by 14.4 N, 7.6N, 8.0N, respectively, total 30N. One of the three muscles was unloaded, and three different valgus torques with a max of 1.5Nm + weight of the forearm was applied.	Valgus angle

Shielding effects of elbow stabilizers during pitching

Although validation of musculoskeletal models is difficult, these models can provide insight in the combined role of the functional and structural stabilizers during pitching. Experimental EMG studies can partly validate these musculoskeletal modelling studies. Therefore, both experimental and musculoskeletal modelling studies should be performed to investigate the shielding effects of elbow stabilizers.

Electromyography (EMG) studies have the potential to study the effect of muscle stress shielding for the UCL. Sisto et al. (1987) recorded the EMG of eight forearm muscles. They

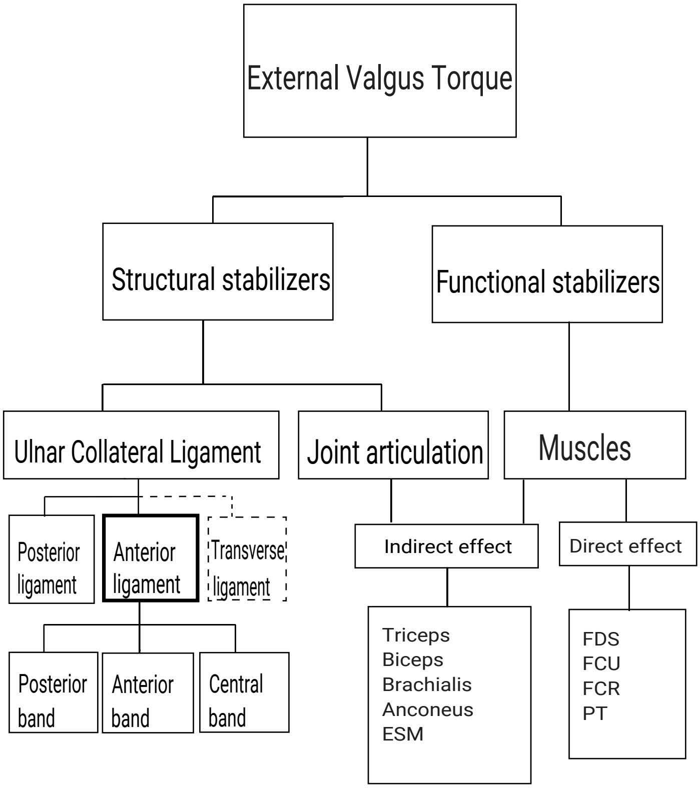

Figure 2. Schematic overview of structural and functional stabilizers which can resist or counteract an external valgus torque according to in-vitro studies. Dashed line: Cannot resist valgus torque but is part of the Ulnar Collateral Ligament.

found that the FDS, FCR, and PT had low to moderate activity throughout the pitch. The peak activities occurred in the late cocking phase (30%, 28%, and 25% of their maximal voluntary contraction (MVC), respectively). In contrast, Digiovine et al.(1992) found that the peak activity of the FDS, FCR, FCU, and PT all occurred in the acceleration phase (80%, 120%, 112% and 85% of their MVC respectively). In high intensity motions values over 100% isometric MVC are not uncommon [46]. These values likely indicate that pitchers can recruit more motor units during an explosive pitching movement than during a static MVC test. In the late cocking phase, the phase of maximum valgus loading, their activity levels were also high (40-50% MVC). Jobe et al. (1984) found that the triceps was highly active during these phases and the biceps minimally. Most of the elbow muscles are bi-articular, which means that movement around another joint influences the muscle activation. This has no influence on the stabilizing effect, because the muscle activity will, due to its joint compression force, have a stabilizing effect around the elbow, irrespective of the movement it is aiming to induce. Figure 3 shows the normalized muscle activity during the different pitch phases. The muscle activity is the mean over all (two or three) studies which measured the respective muscle.

Werner et al. (1993) combined the valgus torque with EMG measurements during pitching. They did not normalize muscle activity, which makes it hard to determine the relative contribution of each muscle. Based on the patterns, they found that the FPM, as well as the anconeus and triceps were active during peak valgus torque and concluded that the FPM could provide varus torque, while the anconeus and triceps may have helped in minimizing UCL load by compressing the joint. This is in line with the in-vitro studies of Seiber et al. (2009) and Morrey et al. (1991).

If we assume a shielding effect of the functional stabilizers, the timing of functional stabilizers is crucial. Unfortunately, all EMG studies provided results that were summarized over the throwing phases and are thus not accurate enough to draw conclusions at which instant the muscles studied actually contribute to reduce UCL stress (Figure 3). Preferably, future EMG research should investigate muscle onset timing in more detail, linking kinematics and kinetics time series.

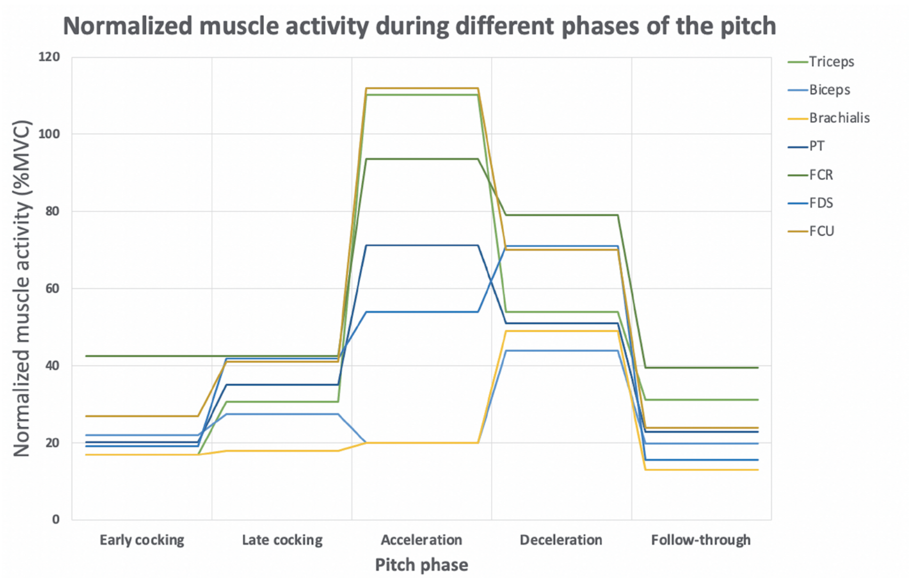

Figure 3. Muscle activity over different phases of the pitch cycle. The lines represent the muscle activity normalized by the maximal voluntary contraction (MVC). The muscle activity is the mean over all (two or three) studies which measured the specific muscle (Sisto et al. 1987, Jobe et al. 1984 & Digiovine et al. 1992)

With the upcoming trend of musculoskeletal modelling, it has become feasible to estimate UCL loading, given a sufficiently accurate elbow model. However, up to now, only one published study [4] investigated the baseball pitch with musculoskeletal modelling. They used an open-source musculoskeletal model with fourteen elbow internal varus muscle-tendon actuators to forward dynamic simulate the baseball pitch. The maximum external valgus torque imposed on the upper arm throughout the pitching motion was 115 Nm. From the simulations, it appeared that the FDS could have the most extensive contribution to counteract the valgus torque, followed by the PT and the FCR, although the model showed that activity appears 40ms after peak valgus torque, probably around the instant of ball release, which is later compared to the rough EMG results. The triceps had the largest contribution during external peak valgus torque. It worked out to be impossible to create enough muscle force to counteract the external torque and the osseous and/ or UCL contributions were also needed. A drawback of the model was the difficulty to combine the ligamentous and muscular contribution in the model, which is a generally recognized limitation of musculoskeletal models to date.

CONCLUSION

The goal of this review was to provide an overview of what risk factors are related to UCL injuries, and to better understand the relationship between the UCL properties and elbow stabilizers with the load on the UCL during pitching, by combining literature of in-vitro and in-vivo studies. In-vitro studies show that the ultimate UCL torque is around 35Nm, whereas in-vivo studies found higher peak valgus torques of 120 Nm during pitching. This mismatch raises the question of why 'only' 16% of the pitchers sustain a UCL injury. The explanation of this mismatch is most likely the underestimation of elbow structures, among which structural and functional stabilizers in inverse dynamic models. In-vitro studies demonstrate the direct UCL shielding potential of the FPM muscles and indirect the interaction of elbow flexor-extensor muscles with the compression force of the joint geometry. EMG studies show muscle activity of the FPM and elbow flexor-extensor muscles during pitching. However, these results are summarized over pitch phases and are therefore not sufficiently accurate to conclude on a UCL shielding effect. Musculoskeletal models show potential to investigate also the effect of joint geometry, next to the muscles. However, the validation of these models is difficult. Future studies should investigate how the external valgus torque is distributed over the UCL and other stabilizers, to quantify the UCL load during pitching.

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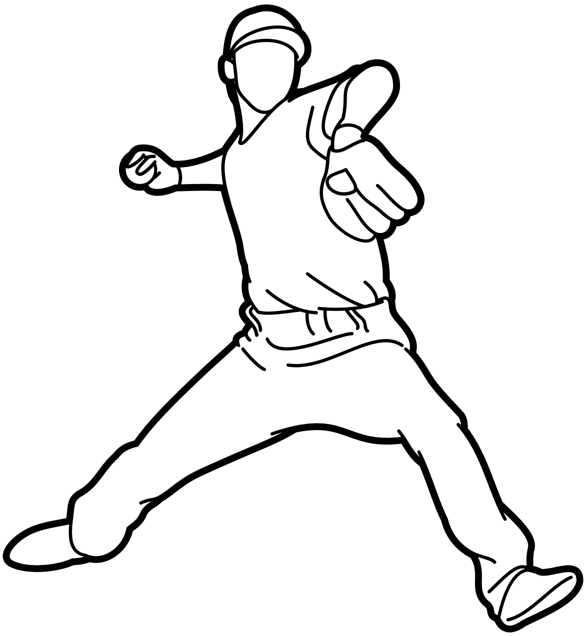

CHAPTER 3

Establishing the role of elbow muscles by evaluating muscle activation and co-contraction levels at maximal external rotation in fastball pitching

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ABSTRACT

Background

Baseball pitching is associated with a high prevalence of ulnar collateral ligament injuries, potentially due to the high external valgus load on the medial side of the elbow at the instant of maximal shoulder external rotation (MER). In-vitro studies show that external valgus torque is resisted by the ulnar collateral ligament but could also be compensated by elbow muscles. As the potential active contribution of these muscles in counteracting external valgus load during baseball pitching is unknown, the aim of this study is to determine whether and to what extent the elbow muscles are active at and around MER during a fastball pitch in baseball.

Methods

Eleven uninjured pitchers threw fifteen fastball pitches. Surface electromyography of six muscles crossing the elbow were measured at 2000Hz. Electromyography signals were normalized to maximal activity values. Co-contraction index (CCI) was calculated between two pairs of the flexor and extensor elbow muscles. Confidence intervals were calculated at the instant of MER. Four ranges of muscle activity were considered; 0% to 20% was considered low; 21% to 40% moderate; 41% to 60% high and over 60% as very high. To determine MER, the pitching motion was captured with a highspeed camera at 240 Hz.

Results

The flexor pronator mass, pronator teres, triceps brachii, biceps brachii, extensor supinator mass and anconeus show moderate activity at MER. Considerable variation between participants was found in all muscles. The CCI revealed co-contraction of the two flexor-extensor muscle pairs at MER.

Conclusion

The muscle activation of the flexor and pronator muscles at MER indicates a direct contribution of forearm muscles crossing the medial side of the elbow in counteracting the external valgus load during fastball pitching. The activation of both flexor and extensor muscles indicates an in-direct contributory effect as the combined activity of these muscles counteract opening of the humeroulnar joint space. We believe that active muscular contributions counteracting the elbow valgus torque can be presumed to relieve the ulnar collateral ligament from maximal stress and are thus of importance in injury risk assessment in fastball pitching in baseball.

INTRODUCTION

Baseball pitching is a sports action that stresses the medial side of the elbow and is associated with a high prevalence of medial elbow injuries [1,2]. The current leader of medial elbow injuries in pitchers is an injury to the medial Ulnar Collateral Ligament (UCL) with 25% of the Major League Baseball pitchers having undergone UCL reconstruction during their career [3][1,2]. It is desired to prevent pitchers from experiencing UCL injuries to save associated costs and increase playability. Understanding the pathophysiological mechanisms through mechanical analyses of sustaining an elbow injury, and more specifically an injury to the UCL, might shed light on effective injury prevention programs.

Inverse dynamics studies show that, when performing a baseball pitch, shortly before shoulder maximal external rotation (MER), as the throwing arm transitions through the arm cocking phase and acceleration phase, the elbow resists its peak load [4–6]. At this instant the elbow is exposed to an external valgus torque of reportedly 60-120 Nm. It is stated that the external valgus torque at the timing of MER is identified as a critical load related to medial elbow injuries [6]. The external valgus torque can be resisted by structural stabilizers, such as joint articulations and ligaments. According to in-vitro studies the anterior band of the UCL is the main structural stabilizer capable of resisting an external valgus torque [7]. In addition, it has been reported that pitchers throwing with a higher external valgus torque have a thicker UCL compared to pitchers who throw with a lower external valgus torque [8], indicating that the UCL is important in resisting the external valgus torque. However, the precise relationship between external valgus torque, UCL load, UCL characteristics and UCL injuries in baseball pitching is unknown.

The literature shows that not only the UCL but also functional stabilizers, such as muscles, are able to counteract the external valgus torques, either direct or indirect [9]. In vitro studies show that the flexor pronator muscle group (FPM), which consists of the m. pronator teres, m. digitorum superficialis, m. flexor carpi ulnaris and the m. flexor carpi radialis, is a significant contributor to counteract an external valgus torque [10–13]. The forearm flexor muscles could have a direct effect in counteracting the external valgus torque during pitching. In addition, the interaction between the functional stabilizers and the elbow joint geometry could have an indirect effect on the valgus torque by increasing the joint compression force [9]. Several in-vitro studies showed that simulated loading of the biceps and triceps brachii significantly decreased the ulnohumeral joint space and thus resist the external valgus torque [12,14]. In addition, a forward dynamic musculoskeletal model showed that simulated activation of the triceps brachii and biceps brachii increased joint contact force [15]. We therefore assume that co-contraction of flexor and extensor elbow muscles could indirectly counteract the external valgus torque indicating an indirect effect. Hence, the biceps, triceps, anconeus and ESM cannot provide direct stability, like the FPM. However, it is unknown whether elbow muscles are active at the instant of MER during pitching and thus can, either directly or indirectly, counteract the external valgus torque.

Electromyography (EMG) studies measured the activity of the elbow muscles during baseball pitching, in either the cocking or acceleration phase of the pitch. Activation of the FPM, biceps and triceps was found in all studies [16–18]. These studies suggest that the muscles in the throwing arm are active at the late cocking and acceleration phase, which includes the critical instant of MER. Unfortunately, all studies averaged the EMG activity over each pitch phase, resulting in limited information on the activation pattern of the muscles potentially related to counteracting the external valgus torque at MER. More detailed EMG data are essential to investigate whether muscles contribute to counteracting the external valgus torque during a fastball pitch. Therefore, the aim of this study is to determine whether and which elbow muscles show activity at MER during a fastball pitch in baseball pitchers. It is hypothesized that: (1) For a direct effect, elbow muscle activation is expected at the instant of MER for the FPM and PT, (2) For an indirect effect, co-contraction of flexor and extensor elbow muscles is expected at the instant of MER.

METHODS

Participants

Eleven experienced male pitchers, with a mean age of 27 (SD 10) years, a mean body height of 1.87 (SD 0.08) m and a mean body mass of 87.4 (SD 17.9) kg participated in this study. Eight pitchers threw right-handed and three left-handed. They started playing baseball at a mean age of 7 (SD 2) years and started pitching at a mean age of 11 (SD 5) years. During the experiments they threw at a mean ball speed of 67 mph (29.95 m/s) (SD 7 mph (3.13m/s)). Two pitchers are playing at the highest level in the Netherlands, three pitchers at the second highest level and the other pitchers at amateur level. At and in the six months prior to the measurements all participants reported to not have experienced musculoskeletal injuries. This research was conducted in accordance with the Declaration of Helsinki and the local ethics committee of the Technical University Delft approved the research protocol. Informed consent was obtained from all participants after being informed of the procedure of the study.

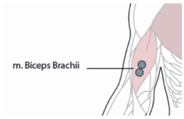
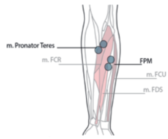
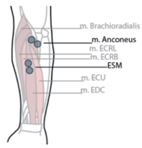
Procedure

The measurements were performed at indoor facilities. Prior to performing fastball pitches, participants had to perform maximum voluntary contractions (MVC) in accordance with the functional characteristics of the muscles (see Table A1 in the appendix), of which the activity was recorded using surface electromyography (EMG). Participants had to slowly increase the force to a maximum effort within 3 seconds, hold it for 3 seconds and relax in 3 seconds again. Each specific MVC was repeated three times, with 30 seconds rest in between. After this, the participants were given an unlimited amount of time to physically warm-up before pitching fastballs at maximum effort. A pitching mound was installed from which the participants had to throw their pitches to a marked strike zone in a net, which was set at the regular pitching distance of 18.3m from the pitching rubber. The participants were instructed to wear their own preferred clothes and baseball glove, but without a shirt during the measurements to avoid interference of the EMG signals. They had to perform fifteen consecutive fastball pitches at maximum effort for data collection. The participant decided when ready to perform the next pitch, the rest was at least 30 seconds.

Data Acquisition

Bipolar surface EMG of six skeletal muscles of the throwing arm was recorded from the flexor-pronator mass (FPM), extensor-supinator mass (ESM), pronator teres (PT), anconeus (Anc), biceps brachii (Bic) and lateral head of the triceps brachii (Tri) (Table 1). Because it is difficult to measure the activity of the wrist flexor muscles individually using surface EMG, we measured the activity of the forearm muscles combined as the FPM and the ESM. A reference electrode was placed at the spinous process of the 7th cervical vertebrae. Electrodes were placed based on the SENIAM guidelines [19]. After skin preparation, bipolar, disposable, pre-gelled Ag/AgCl surface electrodes (Blue Sensor Electrodes N-00-S, Ambu Inc., USA) were placed on the pitchers' skin with a gel-skin contact area of 1 cm^2 for each electrode and an inter-electrode distance of 20 mm. The skin was shaved and cleaned with alcohol before the electrode attachment and the electrode cables were fixated to the skin to avoid cable movement artefacts in the signal and to minimize the risk of loosening of the electrodes from the skin during the pitch movement. The cables of the electrodes were connected to the bipolar active sensor BioPlux research device (Plux biosignals, Arruda dos Vinhos, Portugal), with 16 bits analog channels, a gain of 506 and an analog 25-500 Hz band-pass filter. Data were sampled at a frequency of 2000 Hz. All fifteen consecutive fastball pitches for each participant were recorded in one EMG dataset and locally stored on the BioPlux research device. A LED was attached to one of the channels of the BioPlux research device to annotate each throw and to synchronize EMG with kinematic data. Kinematic data were collected with a high-speed video camera (Sony RX100V, Tokyo, Japan) at 240Hz. The video camera was placed sideways relative to the pitching mound (camera height: 1.25m, distance to mound: ±3.80m). Ball speed of each pitch was recorded from behind the net at home plate distance with a Stalker pro radar gun (Stalker Radar, Plano, TX, USA).

Table 1. Electrode position and orientation.

Muscle(group)	Electrode position and orientation	Electrode placement
m. biceps brachii (Bic)	On the line between the medial acromion and the fossa cubit at 1/3 proximal from the fossa cubit.	
Flexor Pronator Mass (FPM)	At 1/3 distal from the medial epicondyle. In the direction of the line between the medial epicondyle and the middle of the radial and ulna styloid	
m. pronator teres (PT)	At 1/3 distal from the elbow joint between the medial and lateral epicondyle of the humerus. In the direction of the line between the medial side of the elbow and the lateral surface of the radius.	
m. triceps brachii (Tri) (lateral head)	At 1/2 on the line between the posterior crista of the acromion and the olecranon at 2 finger widths lateral to the line.	
m. anconeus (Anc)	Parallel to and below the olecranon on the radial side. In line between the lateral epicondyle of the humerus and the ulna	
Extensor Supinator Mass (ESM)	At 1/3 distal from the lateral epicondyle of the humerus. In the direction of the line between the lateral supracondylar ridge of the humerus and the middle posterior side of the wrist.	

Data Analysis

Kinematics

To synchronize the kinematics with the EMG signals, videos were cut at the onset of the LED light. Video samples at the instant of foot contact (FC), maximal external rotation (MER) and ball release (BR) were visually determined for each pitch using Tracker (version 5.1.3, Open Source Physics). FC was defined as the moment that the foot of leading leg was in contact with the mound, MER was defined as the instant that the shoulder transitioned from an external to an internal rotation and BR was defined as the moment that the pitcher released the ball. The three pitch events were multiplied with an 8.33 (2000Hz/240Hz) sample rate conversion to correspond with the EMG signals.

Electromyography

EMG signals were cut into the fifteen separate pitches using the block signal of 1.5 V of the LED flashlight. The EMG signal of each muscle within the fifteen consecutive pitches was synchronized to the time of MER and cut at 600 samples (0.300 s) prior and 300 samples post MER (0.150 s), resulting in fifteen pitch signal windows of 450ms for six muscles per participant. The EMG pitch signals and MVC signals were concatenated for each muscle. An EMG linear envelope was obtained by rectifying the EMG using the absolute values of the Hilbert transform [20] and applying a fourth-order bi-directional low-pass Butterworth filter of 40 Hz. EMG data were normalized to the highest value of the concatenated filtered linear envelope signal (including both MVC and pitch data) for each muscle. Because EMG data of dynamic movements exceeds the MVC [21], we decided to normalize the data to the highest obtained EMG value from either the MVC or pitch data. So, the EMG data does not exceed the 100%. In line with the study of Cavanagh & Komi (1979), normalized EMG data were time shifted relative to the kinematic data with 50ms to compensate for the electromechanical delay (EMD). Thus, the results represented the muscle activity as an indication of the timing of relative muscle force. To quantify the in-direct effect, a co-contraction index (CCI) was calculated for two muscle pairs (biceps-triceps and FPM-ESM) according to Rudolph et al. (2000):

$$\boldsymbol{CCI = \frac{EMG_{low}}{EMG_{high}} * (EMG_{low} + EMG_{high})} \qquad \text{(Equation 1)}$$

EMG_{low} is the normalized magnitude of the EMG signal for the less active muscle and EMG_{high} for the more active muscle. The CCI index can range from value zero (no co-contraction at all) to two (maximal co-contraction). All EMG data analyses were performed in Python (version 3.7, Python Software Foundation, https://www.python.org/).

Statistical analysis

From the fifteen throws mean and standard deviation of the six normalized EMG signals were visualised over time. To visualize the in-direct effect, the EMG signals of the flexor muscles were labelled as positive and the extensor muscles as negative. In addition, the CCI were visualised over time. At the time instant of MER, the magnitude of the normalized EMG and CCI data was obtained. The assumption of normality was checked with the Shapiro-Wilk test of the EMG data at MER. On group level mean and 95% confidence intervals at MER were calculated to investigate if muscle activity were statistically different from zero. Within subject variability was defined as the 95 % confidence intervals calculated over the fifteen throws. According to Digiovine et al. (1992), four ranges of muscle activity were considered to what extent muscles showed activity. A range of 0% to 20% was considered low; 21% to 40% moderate; 41% to 60% high and over 60% as very high.

RESULTS

After visually analysing signals for artefacts, for instance due to loosening of electrodes, 74 (of the 990) signals from nine (of the eleven) participants were excluded from the analysis. All EMG and CCI data at MER were normally distributed.

Direct effect

The normalized EMG data of the flexor lower arm muscles on group level are shown in Figure 1. Visual inspection shows activity the FPM and PT at the instant of MER. On group level at the instant of MER the average FPM activity is 30.70%, 95% CI: [23, 39] and the average PT activity is 33.0% , 95% CI [25, 41].

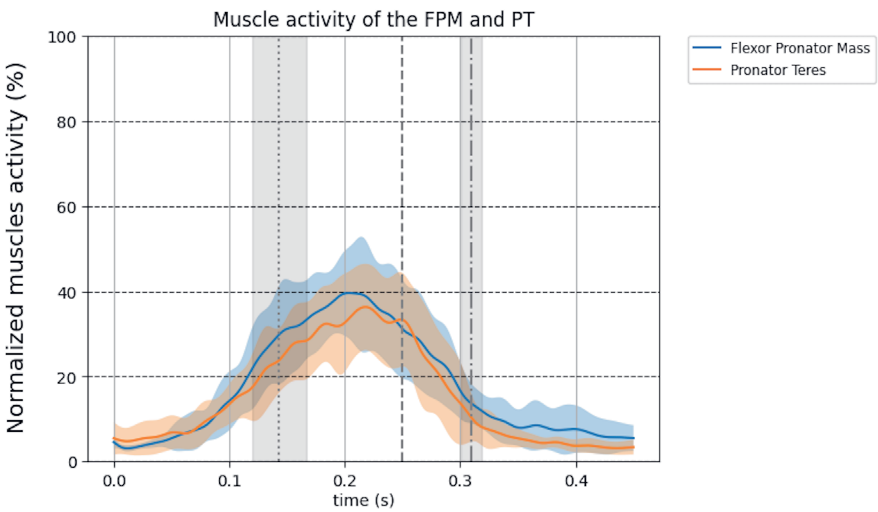


Figure 1. Normalized group level EMG signal time-series for the forearm muscles corrected for EMD (50ms) . The colored thick line in the time series shows the mean over all eleven pitchers and the standard deviation is shown as transparent area around the mean. Blue line: flexor pronator mass, orange line: pronator teres. The three vertical lines represent foot contact (dotted), MER (dashed) and ball release (dot dashed), respectively.

In-direct effect

All EMG data of the flexor and extensor elbow muscles are shown in Figure 2. All muscles show maximal activity between FC and BR, except for the ESM which is most active before FC. Visual inspection shows elbow muscle activity of both flexor and extensor muscles simultaneously at the instant of MER on group level. On group level the average muscle activity at MER of the biceps was 29.8 %, 95% CI [20.0, 39.7], the triceps was 33.5%, 95% CI [24.5, 42.5], the ESM was 24.4%, 95% CI [16.6, 26.2] and the anconeus was 33.7%, 95% CI [26.4, 41.0]. Figure 3 shows the CCI of the biceps-triceps and FPM-ESM during pitching. Visual inspection shows co-contraction at the instant of MER for both pairs. On group level the average CCI was 0.35, 95% CI [0.24, 0.47] for the biceps-triceps and 0.26, 95% CI [0.21, 0.30]) for the FPM-ESM at the instant of MER.

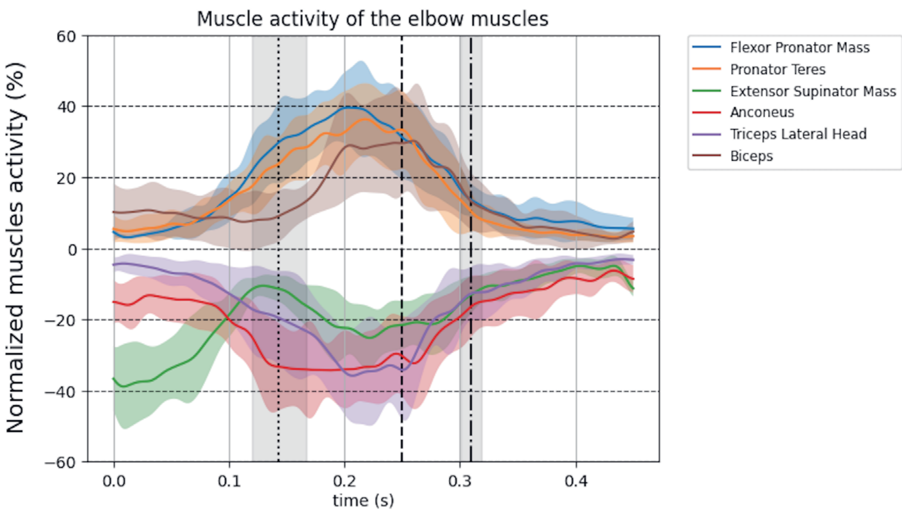


Figure 2. Group level normalized EMG signal time-series for the upper arm muscles corrected for EMD (50ms). The thick line shows the mean over all eleven participants and standard deviation is shown as transparent area around the mean. The flexors are plotted positively on the vertical axis and the extensors are plotted negatively on the vertical axis. Brown line: biceps brachii, blue line: Flexor pronator mass, orange line: pronator teres, green line: extensor supinator mass, purple line: triceps brachii, red line: anconeus. The three vertical lines represent FC (dotted), MER (dashed) and BR (dot dashed), respectively. Be aware: the normalized activity ranges from 0% till 100%, here the y-axis scale ranges from 0% to 60% for better visualization.

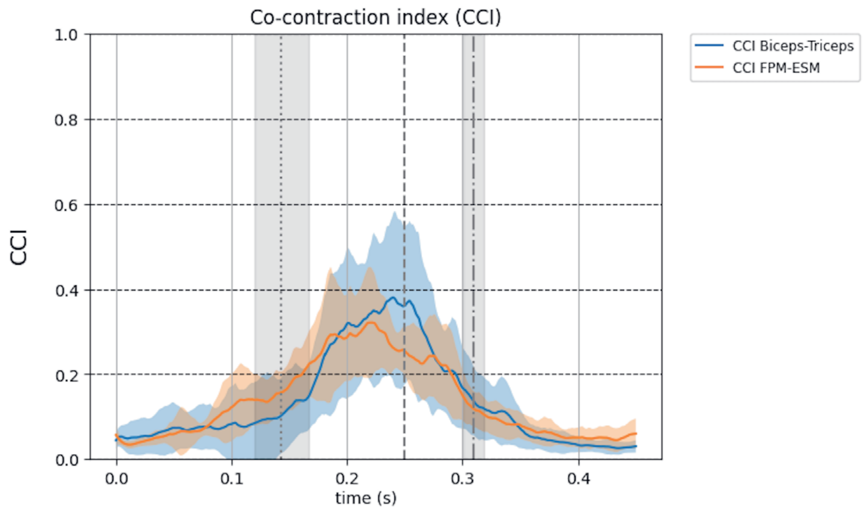


Figure 3. Group level of the co-contraction index of the elbow muscles during pitching corrected for EMD (50ms). The thick line shows the mean over all eleven participants and standard deviation is shown as transparent area around the mean. Blue line: CCI Biceps-Triceps, orange line: CCI FPM-ESM. The three vertical lines represent FC (dotted), MER (dashed) and BR (dot dashed), respectively. Be aware: the co-contraction index ranges from 0 till 2, here the y-axis scale ranges from 0 to 1 for better visualization.

Mean and within subject variability

Figure 4 shows the mean and confidence intervals of each participant for each muscle and CCI at MER. The dots between the two grey vertical lines represent the mean muscle activity for each pitcher. The blue vertical lines show the confidence intervals, representing the within subject variability.

DISCUSSION

The aim of this study was to determine whether and which elbow muscles show activity at MER during a fastball pitch, potentially to (partly) counteract the peak external valgus torque at the instant of MER. Moderate activity is observed in the FPM and the PT, indicating a direct effect. Elbow flexors and extensors are active simultaneously at the instant of MER, indicating an indirect effect. However, the flexor- and extensor muscle activity at MER is different between pitchers, resulting in wide ranges of muscle activity and co-contraction index values.

In-vitro studies show that the flexor pronator muscles are able to resist an external valgus torque at the elbow [12,13,24], although no reports are available describing whether these muscles are actually active at the relevant instant during the relevant pitch phase, i.e. at peak

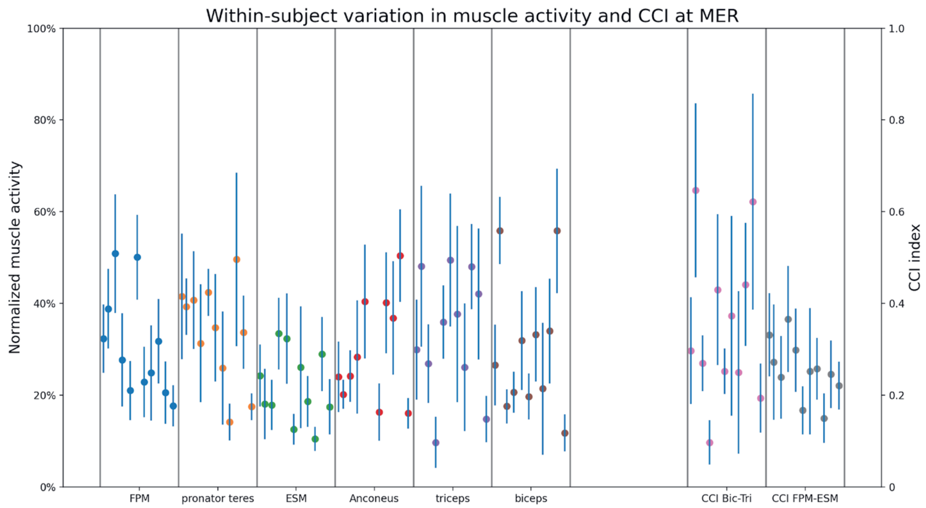


Figure 4. shows the within-subject variation in muscle activity and CCI for all measured muscles and CCI pairs at MER. Blue vertical lines show the confidence intervals calculated over the fifteen thrown pitches. Each blue vertical line within one box (divided by the grey lines), represents the within-subject variation of each individual participant. The dots represent the mean muscle activity of the fifteen thrown pitches for each participant.

external valgus torque. The muscle activity of the FPM and PT observed in the present study at the instant of MER, the instant at which the external valgus torque is estimated to be at its maximum during fastball pitching, strengthens the theory that forearm flexor muscles directly counteract the external valgus torque at MER. The in-vitro studies in combination with the results of our study may indicate that the UCL might not resist the entire valgus torque by itself, but that the forearm flexor pronator muscles are able to counteract the valgus torque at least partly during baseball pitching as well.

Elbow flexor and extensor muscles, together with the joint articulation, could also indirectly affect the mechanical resistance of the external valgus torque at the elbow during pitching (Trigt et al. 2021). In-vitro cadaver studies and forward dynamic model studies showed that the biceps and triceps are important in stabilizing the elbow joint [12,14,15]. Our results show co-contraction of elbow flexors and extensors at the instant of MER during fastball pitching. To quantify the indirect effect, the CCI index was calculated. It is shown that the CCI index by Rudolph et al. (2000) is best correlated with joint stiffness [25], and thus in potentially counteracting an external load. The mean CCI at MER in the present study were 0.35 for the biceps-triceps and 0.26 the FPM-ESM. Similar values were found in a study involving the knee joint, which reported the highest CCI values of 0.4 (SD 0.27) during the loading phase in gait [26]. The knowledge of in-vitro studies and the forward dynamic

3

modelling study in combination with the observed levels of muscle activity of both flexor and extensor muscles at the instant of MER strengthens the theory of elbow muscle co-contraction at the instant of MER having an in-direct effect in counteracting an external valgus torque during fastball pitching in baseball.

The advantage of the CCI applied in the present study is that it considers the magnitude of muscle activity, but the disadvantage is that it calculates the co-contraction only between two muscles instead of all muscles crossing the joint. Using the average muscle activity over the two muscles pairs would result in a biased estimate of the CCI, because muscle sizes and moment arms are not considered. We did not measure the brachialis and brachioradialis, and especially the brachialis might have an important function in counteracting the valgus torque when co-contracting with the extensor muscles, because it is monoarticular, has a small moment arm and a large PCSA.

The literature shows limited information about the anconeus muscle during pitching, and its function is still under debate. It is shown that the anconeus is active in slowly performed elbow extension tasks, but that it has a weak extension function [27]. However, the contribution of the anconeus in explosive movements like baseball pitching is unknown. It could be hypothesized that the anconeus extension contribution becomes more important in explosive movements. Although may be more reasonable, and in line with our results, is that the anconeus might be important in stabilizing the joint via the described indirect effect.

It is not possible to measure muscle force in a non-invasive way. Therefore, the timing of the EMG signals was corrected with 50ms electromechanical delay (EMD) for each muscle and each participant to represent the muscle activity as an indication of timing of relative muscles force in relation to the timing parameters assessed in the present study (FC, MER, BR). The EMD depends on participants and the type of muscle contraction [22]. In the study of Cavanagh (1979) it ranges between 35ms and 77ms. The results of Cavanagh showed that the effect of the muscle type contraction on EMD is subtle, but the EMD between participants showed more variance. Although applying the EMD in a range from 35 to 75ms changes the magnitude but the muscles still show increased activity in that range (Figure 1 and 2), therefore, it will not affect our conclusion that elbow muscles are active and thus able to counteract the external valgus torque.

In this study a considerable difference in magnitude and patterns of EMG between pitchers is found (Figure 4). This could be explained by the fact that this study contains a heterogenous group of pitchers, including different levels of play and age. However, maybe more reasonable in relation with counteracting the external valgus torque is the fact that EMG activity is not directly correlated with muscle force, because EMG does not consider pitcher's muscle properties. For example, pitchers with less muscle activity might have more fast twitch muscle fibers and/or larger PCSA compared to pitchers with more muscle activity.

Thus, next to the muscle activity it is important to be aware of the muscle properties in relation to counteracting the external valgus torque.

The (in)direct effect of elbow muscles at MER is important in understanding and preventing pitching related to elbow injuries in baseball. As the external valgus torque at MER is not only resisted by the UCL, but also counteracted by the muscles overlying the elbow joint, it is important to understand the load distribution over these anatomical structures. Therefore, future research should investigate if pitchers with less elbow muscle force at MER are more prone to injury compared to pitchers with more elbow muscle force. Pitching kinematics and kinetics in combination with the use of musculoskeletal models and EMG measurements could help investigate between-pitcher load distribution of the relevant anatomical structures of the elbow in relation to elbow injury risk.

This study shows elbow muscle activity at the critical moment of pitching. Trainers and coaches should be aware of the shielding effect of elbow muscles in preventing pitchers from elbow injuries. They could include strength and coordination exercises in their training program to optimize the elbow muscles function during pitching. In clinical terms, orthopedics should be aware that the elbow muscles can stabilize the joint and might relieve the UCL from maximal stress in overhead sport motions. This knowledge could be used in return-to-sport programs and to prevent athletes from UCL surgeries.

CONCLUSION

The flexor and extensor elbow muscles are active at MER, the instant at which the external valgus torque is estimated to be at its maximum, during fastball pitching in baseball. The FPM and PT have a potentially direct effect in helping the UCL to counteract the external valgus torque. Co-contraction of the elbow flexor and extensor muscles indicate a possible in-direct effect in counteracting the external valgus torque. We believe that active muscular contributions counteracting the elbow valgus torque can be presumed to relieve the UCL from maximal stress and is thus of importance in injury risk assessment in fastball pitching in baseball.

Data availability
The data underlying this study can be found here: DOI 10.4121/17021966

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APPENDIX

Table A.1. Maximal voluntary contact (MVC) tests. The gray arrow indicates the applied force direction of the participant. The black arrow indicates the direction of the resistance.

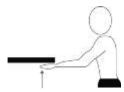
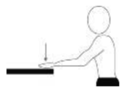
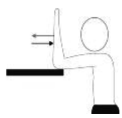
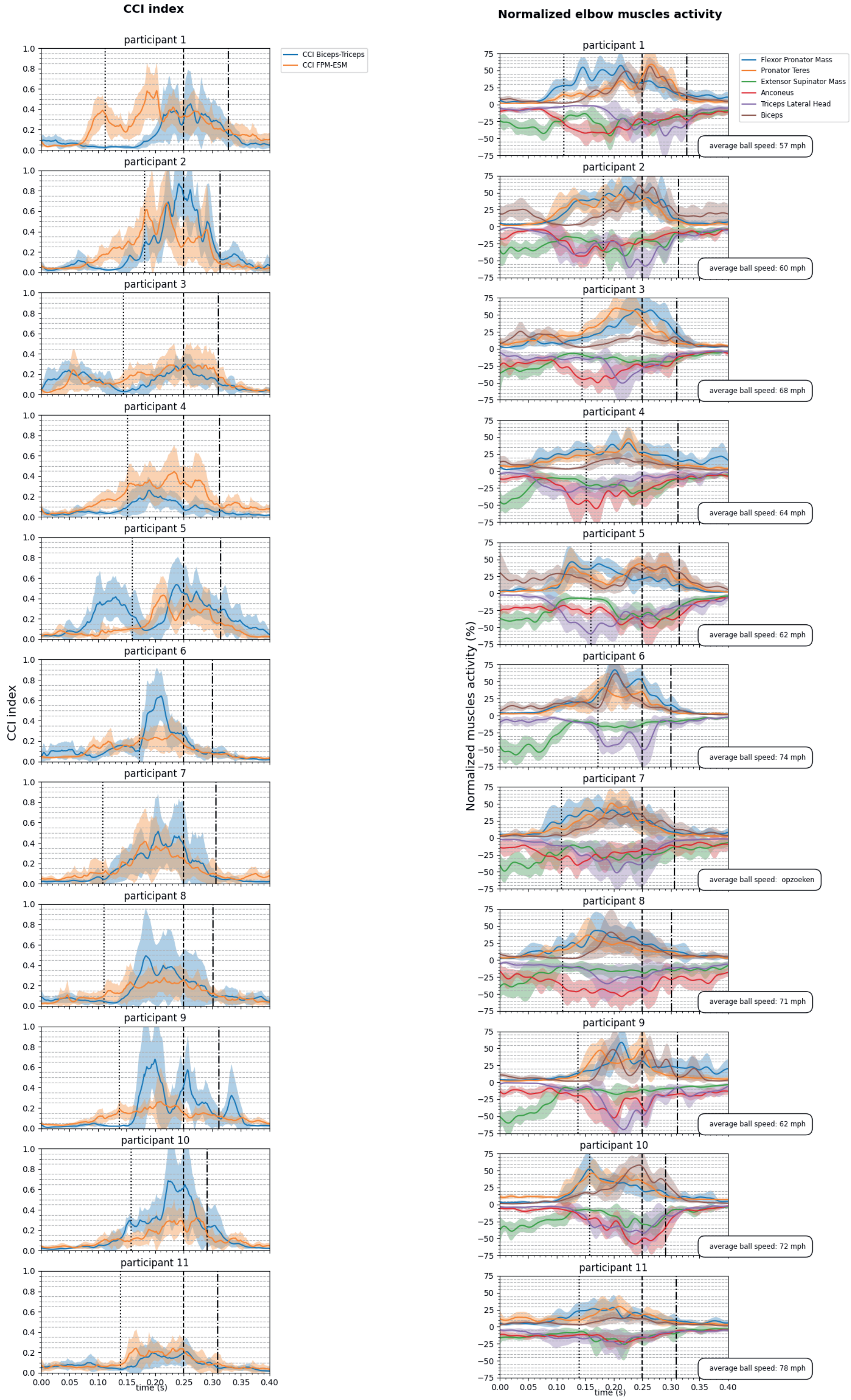
Muscle group	Maximal voluntary contraction test	Illustration
Flexor pronator group (FPM) & pronator teres	Seated or kneeling position in front of a table. With the forearm in approximately 90 °with respect to the upper arm. Participant performs a wrist flexion by pushing the hand palm against the bottom of a ground fixed table. The table functions as static resistance.	
Extensor supinator group (ESM)	Seated or kneeling position in front of the table. With the forearm in approximately 90 °with respect to the upper arm. Participant performs a wrist extension by pushing the back of the hand against the top of the table. The table functions as static resistance.	
M. biceps brachii	Seated or kneeling position in front of the table. With the forearm in approximately 90 °with respect to the upper arm, and the elbow rests on top of the table. One of the researchers apply a static resistance against the forearm while the participant performs an elbow flexion	
M. triceps brachii & Anconeus	Seated or kneeling position in front of the table. With the forearm in approximately 90 °with respect to the upper arm, and the elbow rests on top of the table. One of the researchers apply a static resistance against the forearm while the participant performs an elbow extension.	

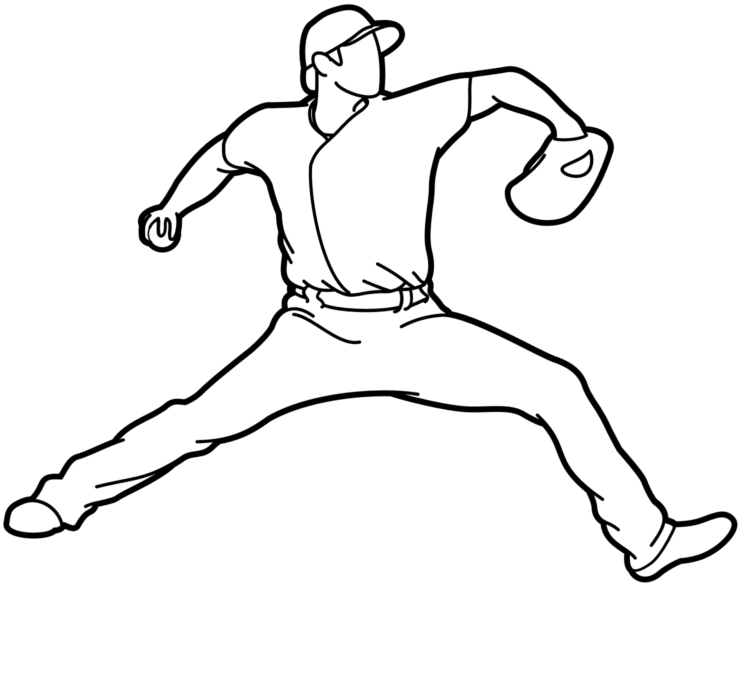
Figure A1. The left panel shows the individual course of the co-contraction index of the elbow muscles during pitching corrected for EMD (50ms). The thick line shows the mean over all fifteen pitches and the standard deviation is shown as a transparent area around the mean. Blue line: CCI Biceps-Triceps, orange line: CCI FPM-ESM. Be aware: the co-contraction index ranges from 0 till 2, here the y-axis scale ranges from 0 to 1 for better visualization.
The right panel shows the individual normalized EMG signal time series for the upper arm muscles corrected for EMD (50ms). The thick line shows the mean over all eleven participants and the standard deviation is shown as a transparent area around the mean. The flexors are plotted positively on the vertical axis and the extensors are plotted negatively on the vertical axis. Brown line: biceps brachii, blue line: Flexor pronator mass, orange line: pronator teres, green line: extensor supinator mass, purple line: triceps brachii, red line: anconeus.
The vertical lines in both panels FC (dotted), MER (dashed) and BR (dot dashed), respectively. ▶


CCI index
Normalized elbow muscles activity
CCI Biceps-Triceps
CCI FPM-ESM
Flexor Pronator Mass
Pronator Teres
Extensor Supinator Mass
Anconeus
Triceps Lateral Head
Biceps
participant 1
average ball speed: 57 mph
participant 2
average ball speed: 60 mph
participant 3
average ball speed: 68 mph
participant 4
average ball speed: 64 mph
participant 5
average ball speed: 62 mph
participant 6
average ball speed: 74 mph
participant 7
average ball speed: opzoeken
participant 8
average ball speed: 71 mph
participant 9
average ball speed: 62 mph
participant 10
average ball speed: 72 mph
participant 11
average ball speed: 78 mph
CCI index
Normalized muscles activity (%)
time (s)

Ik vertel hier
over repetitive pitching.

PART II

Repetitive pitching



CHAPTER 4

Are UCL injuries a matter of bad luck? The role of variability and fatigue quantified

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ABSTRACT

Upper extremity injuries are common in baseball. One of these is the ulnar collateral ligament (UCL) injury. In the field of sports injuries, most research focuses on average kinematics and kinetics between subjects, whereas focusing on within-subject variability appears to be more relevant for determining injury risk. We constructed a simplified explanatory simulation model to illustrate the relationship between within-subject load variability and risk, illustrating how pitchers with a higher load variability are more likely to sustain an injury compared to pitchers with less load variability. Furthermore, the model comprises the (theoretical) effect of fatigue on load variability and injury threshold over time.

INTRODUCTION

Ulnar collateral ligament (UCL) ruptures are common in baseball. Among professional players, more than 10% have had a UCL replacement also called a Tommy John Surgery, during their career. Pitchers have a significantly higher prevalence rate of 16% [1]. The incidences of UCL reconstruction are increasing, especially in young players [2]. To reduce injuries necessitating a Tommy John surgery, a better understanding of the injury mechanisms is important.

Why do 16% of the pitchers sustain a UCL injury, while others do not? Most studies investigate the group averages of kinematic and kinetic variables in relation with performance or injuries, starting from the assumption that these variables relate to overloading of the UCL. It is, however, probably more relevant to focus on within-pitcher variability as well as the average magnitude of load. This assumes that an injury occurs when a peak load exceeds a certain injury threshold and that a large variability, in combination with a high average magnitude, will increase the risk of reaching that threshold. Based on the magnitude of individual variability, some individuals will have a higher risk compared to others. Individuals with lower load variability are less likely to sustain an injury compared to individuals with a higher load variability (Figure 1a). Furthermore, this variability is likely influenced by different factors such as fatigue or intersegmental coordination.

The UCL resists an external valgus torque during the baseball pitch. This external valgus torque stresses the UCL, which counteracts this by an internal varus torque. To determine the UCL injury risk, the UCL load needs to be determined. It is, however, not possible to measure UCL loading directly during the baseball pitch. Therefore, researchers have used inverse dynamic analysis to calculate the varus–valgus torque during the baseball pitch [3], which can be seen as a proxy for UCL loading. At a certain peak load, the UCL will give in or tear; the magnitude of which cannot be concluded from the inverse dynamic analysis. For this reason, researchers have tried to estimate the ultimate peak load and ultimate valgus torques of the UCL with in-vitro studies [4,5]. This in-vitro peak load or ultimate valgus torque can be assumed as the injury threshold.

The purpose of this paper is to illustrate the concept of individual pitcher load variability in relation to injury risk.

METHODS & RESULTS

The UCL ultimate strength as a proxy of the injury threshold

UCL strength has been estimated with in-vitro studies. Most of the in-vitro studies have investigated the ultimate valgus torque that the UCL could resist by applying a torque around the elbow. They found that the UCL could resist a valgus torque of approximately 30 Nm [5,6].

Dividing these torques by the torque arm (the distance between UCL position and the rotation center) indicates the force the UCL has to resist, which unfortunately can be difficult to determine due to unreported or an undefined definition of lever arms. Two other studies used bone-to-bone complexes to investigate the ultimate force, and found values of approximately 260 N to 293 N [4,7]. These studies used adult cadavers with a mean age around 54 years and most likely no history in baseball. While short-term repetitive loading might lead to a decrease in strength, long-term regular loading of a ligament will probably increase its load capacity, which would imply that a strength scaling factor for baseball players might be necessary.

The short-term relationship between regular loading and UCL ultimate strength is unknown. None of the in-vitro studies have investigated the influence of fatigue and creep on the UCL ligament. From animal studies, it is known that rabbit ligaments show non-linear viscoelastic behavior over time [8]. Furthermore, in rabbit ligaments, tensile fatigue loading (cycle- and time-dependent) appeared to be more damaging than creep (time-dependent) [9]. Future research should investigate the influence of adaptation to understand its effect on UCL strength threshold.

Within-pitcher load variability and fatigue

Gaining insight in the magnitude of within-pitcher load variability and an estimated injury threshold will provide more information about the possibility of the occurrence of UCL injuries. To illustrate the influence of variability, and to lay out the basis for a predictive injury risk model, we constructed a simplified explanatory simulation model. In this model, the inputs were the average UCL load (N), the number of balls pitched, the variability of the UCL load (N) (modeled as a Gaussian distribution) and the injury threshold, as well as the influence of time-dependency on the last two variables. We ran this computer simulation model three times to explain the influence of variability and fatigue.

Within-pitcher load variability in relation with injury risk

- Simulation 1: in this simulation (Figure 1a, blue dots), 100 throws were simulated. The injury threshold was set at 260 N based on the in-vitro studies. The UCL load is unknown during pitching, therefore the average UCL load input was 220 N based on 85% of the injury threshold. The variability factor was modeled as an input factor (in this simulation 12) multiplied with a random number extracted from a Gaussian distribution with a zero-mean. Each blue dot represents the simulated theoretical force on the UCL by one pitch. In this particular case, the injury threshold was not exceeded. This is also represented in the histogram of Figure 1b.
- Simulation 2: This involved running the simulation program again (Figure 1a, red dots) with the same average UCL load and number of pitches, but with an arbitrarily increased

variability of 33.3% (input factor of 16). It was shown that the injury threshold was exceeded once at pitch 8. Increasing the variability of the force on the UCL will increase the likelihood of exceeding the injury threshold. This means that a pitcher who throws with a higher variability (Figure 1c) will have a higher injury risk when compared to a pitcher with a lower variability (Figure 1b).

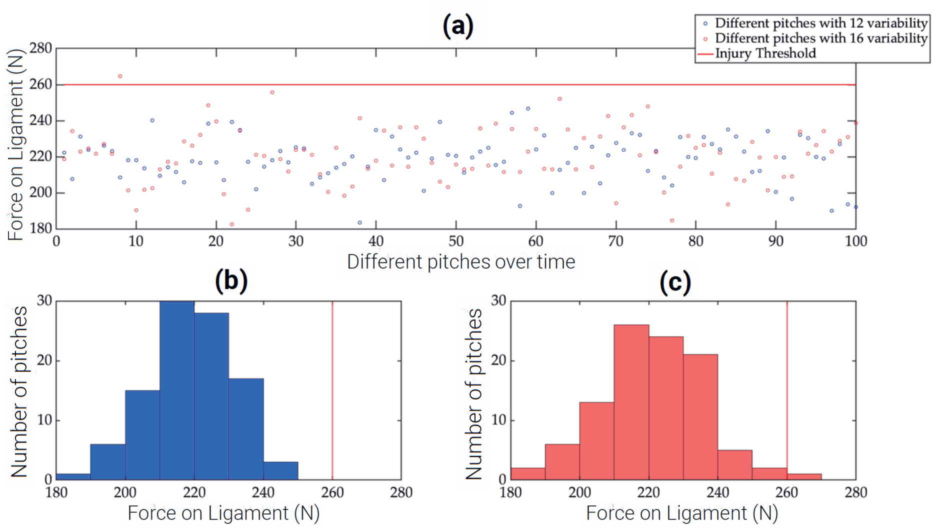

Figure 1. (a) The force on the ligament by different of pitches over time. Blue dots: data from simulation 1 with a low variability; red dots: data from simulation 2 with an increased variability. Red line: injury threshold. (b) The force distribution of simulation 1. (c) The force distribution of simulation 2 with an increased variability. Red vertical line in both lower panels: injury threshold.

In the above simulation, program time had not yet been considered. However, it is known that the number of pitches thrown per inning, game or season have frequently been associated with higher injury risks in UCL injuries [10,11]. This could mean that fatigue will increase load variability; conversely, it will decrease the injury threshold. Within one training session, pitchers show fatigue during pitching, which can be seen in kinematics and kinetics [12]. Fatigue could have an influence on the variability of the UCL loading. Unfortunately, the influence of fatigue on load variability has never been investigated by means of experimental studies. Based on the idea of maintaining performance, compensation will occur which will increase the UCL load, although due to a reduced load capacity the UCL load will decrease. Based on this educated estimate, we assume that the relation between load variability and fatigue is non-linear. Therefore, we modeled this as a quadratic function with an intercept of 1 (Figure 2a, blue line) and multiplied with the variability.

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The injury threshold could change over time within a training session or match and between trainings and matches, which will result in a positive or negative adaptation. Within a training session or match, the load capacity of the UCL will probably adapt negatively due to repetitive movement and fatigue. Based on the in-vitro studies discussed in section 2 [8], we added the non-linear effect of fatigue to the injury threshold. This non-linear effect was modeled as a quadratic function and subtracted from the in-vitro peak injury threshold of 260 N (Figure 2a, red line).

- Simulation 3: In the third simulation the same input as simulation 1 was used, but this time the influence of fatigue was added to the UCL load variability and the injury threshold. The simulation showed an increased variability and a decreased injury threshold over time, which results in a higher chance of sustaining an injury.

This explanatory simulation model will be used in the future as the basis for a feedback tool, although the model will of course need more reliable input (and/or output) variables to be useful for prediction purposes. Most important is the input of the UCL loading during every pitch. In the simulations, the average UCL load was estimated based on 85% of the injury threshold. However, to predict the injury risk for an individual pitcher, the UCL load has to be estimated in vivo.

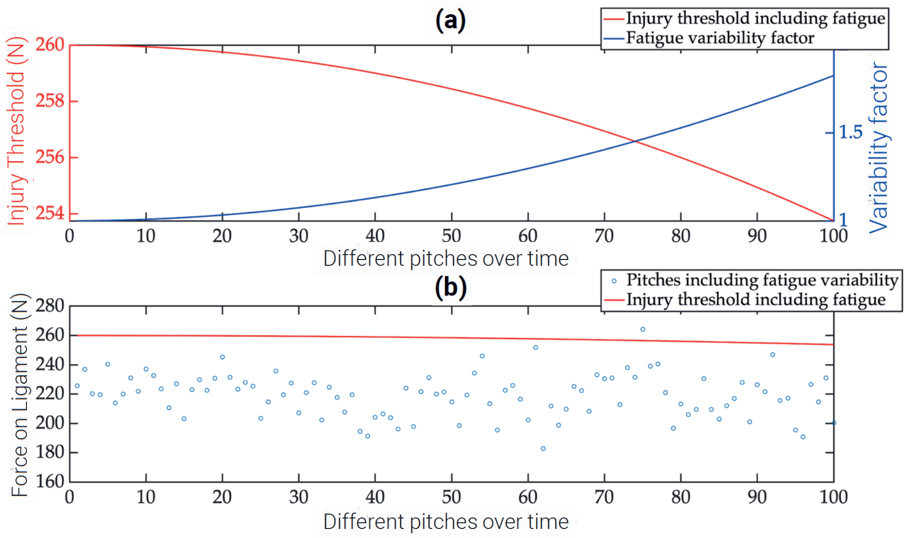

*Figure 2. Data for simulation 3. (**a**) Blue line: non-linear fatigue variability factor over time. Red line: Non-linear negative adaptation of the injury threshold within a training/match. This curve is also represented in the lower panel. (**b**) The influence of a higher load variability on the UCL over time due to fatigue. Red line: the injury threshold, influenced by a non-linear negative adaptation within a training session or match.*

UCL loading during the baseball pitch

The UCL force cannot be measured directly during pitching. Therefore, inverse dynamics were used. With the upcoming trend of musculoskeletal modeling, it becomes possible to calculate the UCL loading in more detail, although these models are not well validated for high-end sports applications. As a consequence, many studies on UCL load use the elbow valgus torque as a proxy for UCL load in relation to injuries. In multiple studies, across various levels of pitching and ages of the pitcher, the peak external valgus torque is in a range of 45–120 Nm [3].

From some recent publications the kinematic variability within pitchers can be estimated [13]. However, none of these studies have investigated the within-pitcher variability of the UCL loading or an equivalent of UCL loading. For a predictive model on injury risk, it is adamant that the within-variability of the UCL loading is known. There is also a need for more insight into the influence of fatigue on UCL load. Birfer et al. (2019) have shown that fatigue is linked to pain, injuries and kinematics [14]. However, the influence of fatigue on the variability of the UCL loading is unknown.

DISCUSSION

The purpose of this paper is to outline a model for the prediction of injury risk in pitching. The simplified explanatory simulation model illustrates the multicausality of injury risk, as well as the time-dependency of this risk.

Using the available results of in-vitro studies, educated guesses can be made for the model parameters, while the results from the inverse dynamics in the baseball pitch can be used as indication for the variability on UCL loading. Using the external valgus torque seems practically more achievable than calculating the UCL force. However, this torque exceeds the ultimate valgus torque of the in-vitro studies in every pitch with at least 15 Nm. These differences may be due to the assumptions in the inverse dynamic models, which are mainly based on segment fixed three degrees of freedom models. Most studies assume the rotation center in the middle between the lateral and medial humeral epicondyle, although the exact rotation center in the elbow is unknown. To determine the influence of this assumption, the varus–valgus torque was estimated by inverse dynamics with three different simulated rotation centers during a baseball pitch: in the middle between both epicondyles, 90% in the direction of the lateral epicondyle, and 90% in the direction of the medial epicondyle (Figure 3a). Details of the inverse dynamic method can be found in the study of Leenen et al. [15]. The results show small differences over time; however, at the instant of the peak external valgus torque it is negligible, which does not explain the torque differences between in-vitro and inverse dynamics. The center of mass position is, for example, more important in terms of peak external valgus torque (Figure 3b). Joint geometry and/or muscle forces are in principle able to resist at least part of the elbow external valgus torque and might explain this difference. Several forearm muscles have the potential to resist the external valgus torque [16]. The muscle onset of these muscles could influence the load distribution on the UCL. For instance, if the activation is inappropriate, the UCL will be stressed more. However, information about the exact muscle onset in relation to the peak external valgus torque is absent due to the generalization over phases of the pitch cycle. Therefore, future studies should investigate the potential shielding effect of muscles around the elbow during the baseball pitch. In conclusion, the external valgus torque is most practical as an input for the model; however, we need to understand the distribution of this torque over UCL, muscles and joint geometry.

The literature shows that fatigue is associated with injuries, and, therefore, it is likely that fatigue within one training session or match increases the load variability and decreases the injury threshold over time. When fatigue was added to our model, the likeliness of exceeding the injury threshold increased. For now, the influence of fatigue on the injury threshold was modeled as a quadratic non-linear effect based on animal studies. The exact non-linear relation of fatigue to the UCL loading should, however, be investigated in the future. The same should be done for the influence of fatigue on load variability.

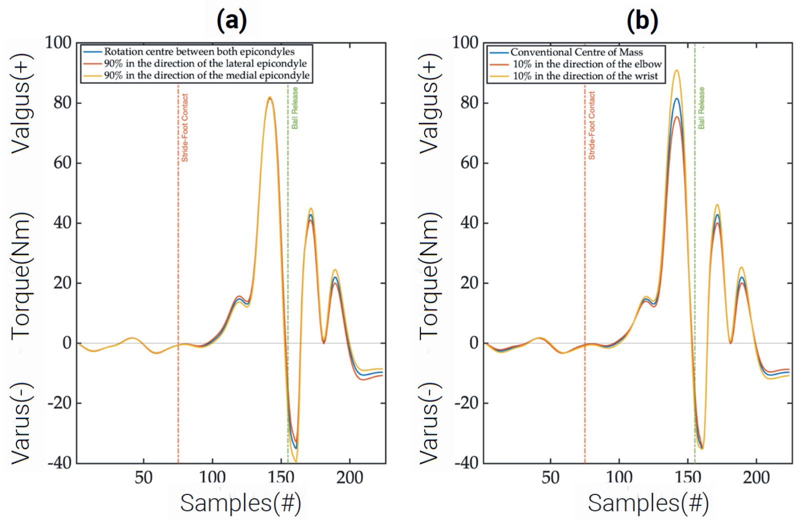

Figure 3. The effect of the location of the choice of the elbow rotation center during a baseball pitch (23 year-old pitcher, ball speed: 83mph) on the varus–valgus torque. (a) One baseball pitch with three different simulated rotation centers. (b) The effect of the position of the center of mass on the varus–valgus torque, conventional simulation (blue line), based on Zatsiorsky regression equations [17].

CONCLUSION

Investigating the individual load variability of pitchers shows its potential toward injury prevention. All pitchers are at risk of sustaining an injury; a higher load variability, higher magnitude and longer exposure all increase this risk. To develop a predictive model for this risk, more information on all parameters is needed, but probably most importantly are those on the magnitude of the variability component.

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CHAPTER 5

Quantifying within-individual elbow load variability in youth elite baseball pitchers and its role in overuse injuries

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ABSTRACT

Medial elbow overuse injuries are rising in baseball. The external valgus torque magnitude is a possible risk factor for medial elbow injuries. The magnitude on its own cannot explain why one pitcher sustains an injury and another does not. Therefore, the aim of this study is to describe the within-individual external valgus torque variability and to determine whether the within-individual external valgus torque variability can be described by a Gaussian distribution. Eleven youth elite baseball pitchers threw twenty-five fastball pitches. Body kinematics were measured with VICON motion capture at 400 Hz. Elbow valgus torques of the total 270 pitches were calculated with a custom-made inverse dynamic model in Python. Visual inspection and the Shapiro–Wilk test were performed to test for the within-individual elbow valgus torque normality. The results showed that within-individual valgus torque variability was present in pitchers and differed among pitchers. Furthermore, it was shown that the within-individual valgus torque variability was normally distributed in nine out of eleven subjects. In conclusion, the presence of and differences in within-individual elbow load variability among baseball pitchers can be useful variables as they might be related to overuse elbow injuries.

INTRODUCTION

In baseball, faster and more accurate pitches increase the chances of beating the batter and thus winning the game. Professional pitchers can throw a baseball, accurately, at speeds over 100 mph. Fast pitches—often at maximal effort—produce high loads on the body, especially on the throwing arm. The pitchers' body parts are exposed to these high loads repetitively in practice and competition. The combination of these high loads and the repetitive nature of the pitch motion induces upper extremity injuries [1]. The most common upper extremity injury is the medial Ulnar Collateral Ligament (UCL) sprain or tear. In Major League Baseball, the highest level of baseball competition in the USA, 25% of the professional pitchers sustain a UCL injury during their career [2]. In addition, UCL reconstructions—a treatment modality for UCL tears—are reported with a yearly incidence of 4.4% in collegiate pitchers [3]. The number of UCL reconstructions has increased substantially at all levels of play over recent years [4]. It is therefore important to prevent athletes from injuries such as UCL injury.

In a systematic review, Bullock et al. [5] investigated biomechanical factors that are associated with elbow injuries. They concluded that elbow valgus torque and early trunk rotation are positively related to UCL injuries. In addition, in a professional group of pitchers, it was found that maximum ball speed is associated with UCL injuries [6]. Thus, reducing elbow valgus torque while maintaining ball speed—for example, by the use of a "proper" kinetic chain [7,8]—would be the best way of reducing UCL injuries. While the positive association between valgus torque and ball speed at group level is weak, it is considerably stronger on the individual level [9]. Reducing elbow valgus torque without loss of performance will, however, be complex at the least.

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As ball speed and elbow load (i.e., elbow valgus torque) are positively associated with UCL injuries, one could argue that recreational pitchers, who throw slower and with less elbow load, should report fewer UCL injuries compared with professional pitchers. However, this lower level of play also shows a high prevalence of UCL injuries [3]. In addition, within a homogenous group such as professional baseball pitchers, the average individual level of ball speed or elbow load cannot explain why 25% sustain a UCL injury and others do not, assuming that the individual magnitude is similar in this homogenous group of professionals. Most of the aforementioned studies analyzed a single pitch [10] or the average of the fastest three–five pitches [11,12], neglecting to consider the within-individual variability in ball speed and elbow load. Assuming that reaching a critical (peak) value of valgus torque is a major determinant in UCL injury, this magnitude will depend on the average torque level as well as the within-individual variability of this torque [13]. Information on both parameters is therefore necessary.

A simple explanatory computational model illustrates that a higher within-individual (elbow) load variability increases (elbow) injury risk [13]. We modeled the load as a Gaussian distribution with an average, standard deviation, and different numbers of pitches as inputs. In this model, the average and standard deviation are interpreted as the load magnitude and within-individual load variability, respectively. Practice shows that individual pitchers throw baseballs at various speeds. It is, therefore, also likely that the various individual pitches (within for instance a game, practice, or season) are associated with a variation in (peak) elbow load. However, the characteristics of the distributions of the within-individual variability of the elbow load are unknown. If, for instance, it can be established that these distributions of individual variability can be described as Gaussian distributions, individual values of means and standard deviations of elbow load can be used to model each individual pitcher's risk of suffering an elbow injury.

To date, it is still not possible to measure elbow load, and more specifically, UCL load, during pitching. However, inverse dynamic models can estimate the external valgus torque as the best proxy for UCL load [5,14], which can thus be used as a parameter for the study of within-individual variability in elbow load.

Therefore, the aim of this study was to describe the within-individual external valgus torque variability of full effort fastball pitches of elite youth baseball pitchers and determine whether the within-individual external valgus torque variability can be described by a Gaussian distribution.

METHODS

Participants

Data were collected from eleven male Dutch national (AAA) pitchers, at a mean age of 17.4 years (SD 2.2, range 15–23). Mean body mass was 80.6 kg (SD 11.7, range 68.2–107.0), mean body height was 186.7 cm (SD 6.3, range 177.0–194.0), and mean ball speed was 76.6 mph (SD 3.19, range 67–83). These elite youth pitchers are the best pitchers of their age group in the Netherlands. Nine pitchers threw with their right hand, while two pitchers threw with their left. All participants were healthy and experienced no pain, soreness, or range-of-motion restrictions. Before involvement in the study, participants were informed of the procedure and study aims and informed consent forms were signed. This research was conducted in accordance with the Declaration of Helsinki and the local ethics committee of the Faculty of Behavioural and Movement Sciences at the Vrije Universiteit Amsterdam approved the measurement protocol (reference number: VCWE-2019-033).

Procedure

The measurements were performed at the campus indoor facility of the Royal Dutch Football Association. The pitchers wore sneakers, athletic stretch shorts, catching gloves, and no shirts. Forty-three reflective markers (10 mm diameter) were attached with double-sided tape directly on the skin at bony landmarks. The pitchers were given an unlimited amount of time to perform their warm-up, including running, stretching, and a specific throwing session. Next, they threw several pitches off the mound to become familiar with the research setup. Once the pitchers were ready, they were instructed to throw fastballs as fast and as accurately as possible. The time between each pitch was not controlled but regulated by the pitcher himself, like in a normal game. To investigate the within-individual load variability, the pitchers threw 25 fastballs. The pitchers threw from a pitching mound towards a square strike zone (height 0.64 m; width 0.38 m) 0.55 m above the ground at a regular game distance of 18.44 m.

Data acquisition

Marker positions were captured using a Vicon eight-camera motion capture system (model V5; Vicon Motion Systems Ltd., Yarnton, UK) sampled at 400 Hz and stored on a local computer. The ball speed of each pitch was captured from a position next to the strike zone with a radar gun (Stalker Radar, Plano, TX, USA) pointing in the direction of the pitcher.

Data analysis

Three-dimensional marker position data were withdrawn in x, y, and z coordinates from the Vicon system, and all the calculations were performed in Python [15]. All data were analyzed between foot contact and ball release, which includes the critical moment of peak external valgus torque. Foot contact was defined as the moment that the forward velocity of the toe was smaller than 0.3 m/s. Ball release was defined as the moment that the wrist exceeded the position of the elbow in the forward direction. The data were interpolated with a 3rd order cubic spline polynomial and filtered with a 4th order Butterworth filter with a cut-off frequency of 12.5 Hz. If a marker flew off before ball release or if a marker could not correctly be reconstructed, the corresponding pitch was not included. Each trial was visually checked for errors and mistakes. Additionally, participant 11 was not allowed, due to pitching restrictions in his training schedule, to throw more than 20 full-effort pitches. Altogether, 250 of the total 270 pitches performed were used for analysis.

Inverse dynamics

For the hand and forearm, an anatomical local coordinate system was made according to the ISB recommendations [16]. The following bony landmarks on the throwing arm were used: third proximal interphalangeal, ulna processes styloid, radius processes styloid, lateral humeral epicondyle, and medial humeral epicondyle. Positions of the centers of mass and the moments of inertia were estimated according to Zatsiorsky (2002) [17] and De Leva et al. (1996) [18]. The baseball was modeled with a mass of 0.145 kg attached to the hand, where the ball mass linearly reduced by 10% over the last ten samples (0.025 s) before ball release. The elbow joint torque was expressed in the anatomical local coordinate system of the elbow, located in the middle of the lateral and medial humeral epicondyle. Using this anatomical coordinate system with the segment data and with the scaling factors of De Leva et al. (1996) and Zatsiorsky et al. (1990), the kinetics of the segments were calculated [17–19]. Elbow joint torques were calculated using the top-down inverse dynamic analysis based on the Newton–Euler equation of motions, starting in the hand of the throwing arm. The external elbow valgus torque was calculated as a time series for each single pitch between foot contact and ball release. Subsequently, the peak external valgus torque was obtained from this time series.

Statistical analysis

The peak external valgus torque values of the series of pitches of each participant were visually checked for normality with Q–Q plots (see appendix) and tested with the Shapiro–Wilk test. A ridgeline density plot was made for the distribution of the external valgus torque for each participant. The ridgeline density plot included the original data of the external valgus torque. The measures of central tendency and dispersion were calculated. If the data were normally distributed, the standard deviation was used to indicate within-individual elbow valgus torque variability. In addition, a normal distribution was calculated from the external valgus torque mean and standard deviation for each participant and added to the figure with the individual density plots. All statistical analyses were performed in Rstudio (version 2022.2.0.443) [20].

RESULTS

Within-individual valgus torque magnitude and variability

Figure 1 presents the density plots and normal distributions of the (peak) external elbow valgus torque values for the series of 17–25 fastball pitches for each of the eleven participants. The descriptives and normality test results are shown in Table 1. The Shapiro–Wilk test revealed that the external valgus torque scores in nine of the eleven participants were normally distributed. The scores of participants 6 and 9 did not show a normal distribution. The scores of participant 6 were positively skewed and the scores of participant 9 were negatively skewed. The skewness of both participants is visualized in Figure 1. The Q–Q plots of the eleven participants are attached in the appendix.

Visual inspection of Figure 1 and the measures of central tendency and dispersion in Table 1 show differences between pitchers in within-individual external elbow valgus torque variability and the actual location of the distribution (i.e., overall elbow load magnitude).

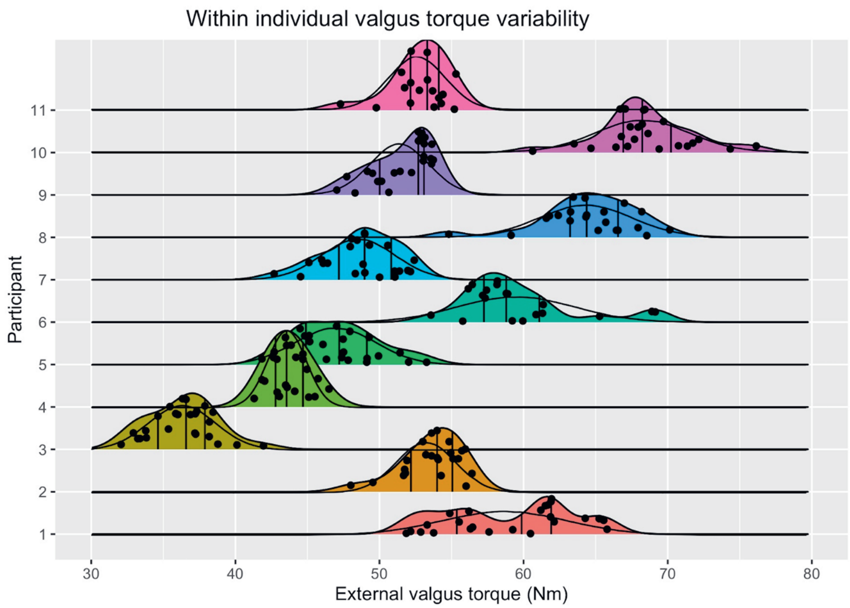

Figure 1. Density plots and matching normal distributions of the within-individual variability in external elbow valgus torque. The participants are shown on the y-axis and the external elbow valgus torque on the x-axis. Each color represents a participant. The dots show the original data of each external valgus torque of a single pitch. The height of the dots is randomly jittered in the density plot. The three vertical solid lines inside the density plots show the 25th, 50th, and 75th percentile of the distribution, respectively. The thin line inside the density plot shows the modeled normal distribution based on the distribution's mean and standard deviation.

*Table 1. Descriptives of the set of scores for each participant for their series of (peak) external elbow valgus torque. The two columns on the right show the results of the Shapiro–Wilk test. SD = standard deviation; IQR = inter quartile range; * = significant.*

Participant	Analyzed Pitches	Mean	Median	SD	IQR	Skewness	Kurtosis	Shapiro–Wilk Test	
									Sig.
1	24	58.91	59.86	4.40	6.55	−0.07	−1.27	0.93	0.11
2	25	53.40	53.61	2.07	3.04	−0.73	0.15	0.95	0.27
3	25	36.35	36.58	2.34	3.25	0.17	−0.26	0.98	0.83
4	23	43.68	43.55	1.34	2.00	0.20	−0.68	0.98	0.94
5	24	47.07	47.21	2.82	4.23	0.39	−0.52	0.97	0.68
6	19	59.68	58.79	4.08	4.15	1.11	0.57	0.88	0.02*
7	23	48.67	48.96	2.55	4.65	−0.51	−0.41	0.96	0.39
8	23	64.54	65.10	3.25	3.33	−1.01	1.65	0.94	0.16
9	23	51.53	52.69	2.05	3.22	−0.76	−0.71	0.87	0.01*
10	24	68.51	68.28	3.25	2.98	0.08	0.71	0.97	0.61
11	17	52.77	53.31	1.96	1.97	−1.21	1.44	0.90	0.07

DISCUSSION

The aim of this study was to quantify the within-individual elbow valgus torque variability when pitching fastballs in elite youth baseball pitchers. The results showed that within-individual elbow valgus torque variability is present in pitchers and differed among pitchers. In the majority of these pitchers, the variability can be described as a Gaussian distribution.

Pitching at full effort produces slightly different elbow valgus torques between fastball pitches within a pitcher. As expected, and in line with other studies, the magnitude (average) of the elbow valgus torque was different between pitchers, showing the between-pitcher variability [8,11,21]. The group average elbow valgus torque in this study population was 53.19 Nm (SD 9.34; range: 36.35–68.5). Similar valgus torques were reported in other studies with comparable ball speeds and study population [8,11]. In these studies, the valgus torque magnitude differences between pitchers has been regularly reported, but the within-individual valgus torque variability has mostly been neglected. In our study, we show that this within-individual valgus torque variability is present in pitchers and differs between pitchers ranging from 1.34 Nm to 4.40 Nm (Figure 1). All pitchers were instructed to throw 25 full effort fastballs, and some pitchers were able to throw with less valgus torque variability compared with others. It is known that within-individual variability is smaller compared with between-individual variability [21]. The magnitude (average) external valgus torque between pitchers can be explained mainly by personal characteristics (body length, mass), motivation, well-being, fatigue, and technique (kinetic chain, energy flow), whereas the within-individual valgus torque variability can mainly be explained by motivation, technique, and fatigue. So, in addition to the magnitude (average) valgus torque, the within-individual valgus torque variability is also different between pitchers.

A higher valgus torque is considered to lead to an increased UCL injury risk, according to previous research [8,10,22]. Within a homogenous group of professional pitchers, 25% sustained a UCL injury [2]. The valgus torque magnitude on its own cannot completely explain this percentage, as all professional pitchers show high valgus torques. To explain this prevalence, the within-individual load variability and the injury threshold are both important metrics to include [13]. The injury threshold in this model is the maximal load the UCL can sustain before it strains or tears. The demonstrated within-individual valgus torque variability and the fact that this differs between subjects is a step towards validating the injury model of van Trigt et al. (2020). However, it is suggested that pitchers who throw with a higher magnitude and within-individual variability of valgus torque might have—but do not necessarily have—a higher chance of sustaining an injury, because the injury threshold is also of importance [13] (Figure 2). It is important to mention that we did not investigate the relationship between valgus torque variability and injuries.

In the model of van Trigt et al. (2020), a load distribution is formed with a load average

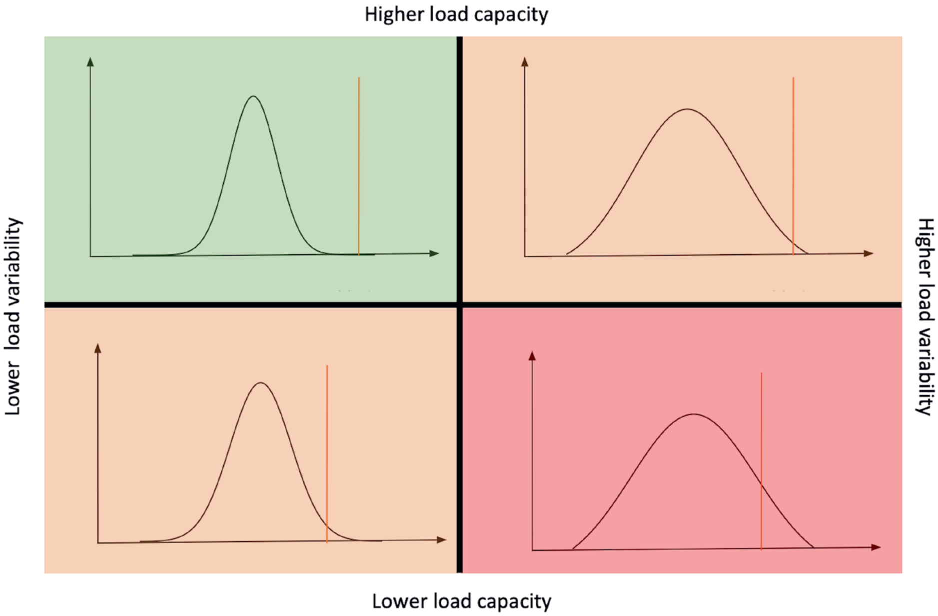

Figure 2. Schematic overview of within-individual elbow load variability (width of the normal distributions) and injury thresholds (red vertical lines). All four quadrants have the same load magnitude (average), shown as the vertical dashed lines. The horizontal axis of the quadrant shows the load variability, and the vertical axis shows the load capacity. The state on the left top panel shows the lowest chance, the right top and left bottom have the same chance, and the right bottom has the highest chance of sustaining an injury. Be aware that a shift in the load magnitude is also possible, but not represented here.

and standard deviation. The results showed that the elbow load distribution in nine out of eleven pitchers could be described as a Gaussian distribution. The standard deviation of this Gaussian distribution can be used as a parameter to quantify the within-individual load variability. This study shows that, based on 25 thrown pitches, an individual load distribution can be built with the within-individual load variability and the load magnitude (average), which can be used for injury assessment.

Longitudinal studies have shown that fatigue influences injury risk [23,24]. Thus, it is too simplistic to assume that the load magnitude, load variability, and injury threshold are fixed parameters over time and are not influenced by, for example, fatigue. It was found that the development of fatigue over time increases the external valgus torque magnitude [25], indicating a shift of the load distribution toward the injury threshold. However, it is unknown whether fatigue also influences the within-individual load variability on a micro-level (within a session) or macro-level (between sessions). Executing a study that investigates fatigue in relation to load variability and the effects on an estimated injury threshold based on our model could provide us with new insights.

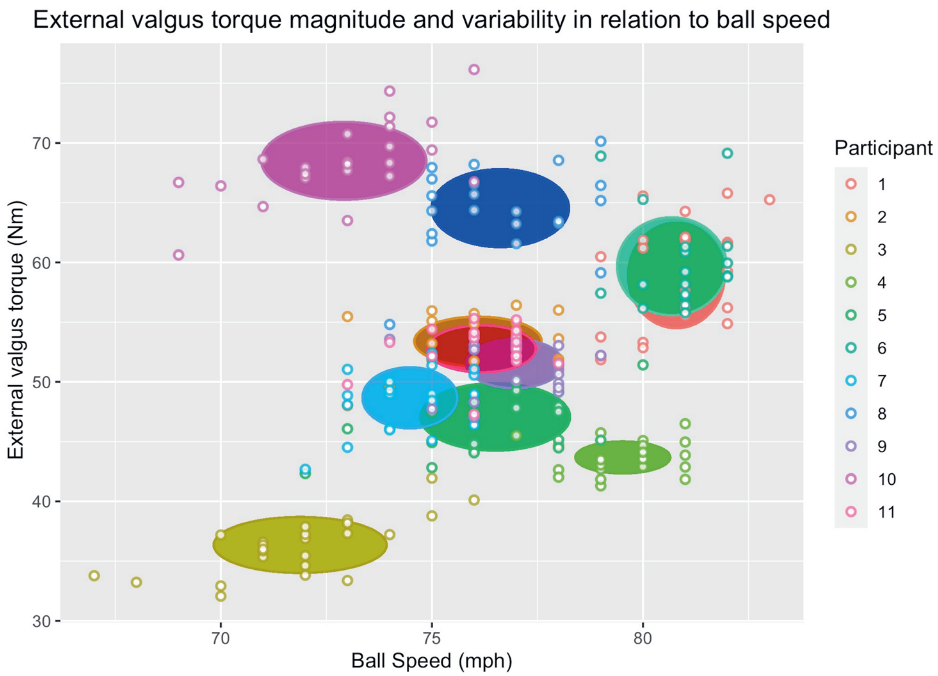

Figure 3. The relationship between ball speed and valgus torque. Every dot is a single pitch of a participant. Each color represents a participant, corresponding with the colors in Figure 1. The ellipses show the within-individual external valgus torque variability and the ball speed variability. The height of the ellipse is twice the standard deviation of individual scores of the external valgus torque, and the width of the ellipse is twice the ball speed standard deviation. The center of the ellipse is the mean of the scores of the external elbow valgus torque and ball speed of a single participant.

In terms of practical implications, the presence of within-individual load variability raises the question of whether this load variability is also related to performance. We, therefore, performed a post hoc analysis and analyzed how the pitchers with load variability were distributed in a graph displaying the relationship between ball speed and external valgus torque (Figure 3). Each dot in Figure 3 represents a single pitch and each color represents a pitcher, corresponding with the colors in Figure 1. On a group level, a weak relationship between external valgus torque and ball speed is present. When individual characteristics are included, this results in a much stronger relationship, which is in agreement with the study of Slowik et al. (2019) [9]. The heights of the ellipses, indicating the within-individual load variability, are randomly scattered in this graph. Linear regression showed that, unlike the valgus torque magnitude, the within-individual valgus torque variability is unrelated to the pitcher average ($p = 0.309$, $R2 = 0.1146$) or maximal ($p = 0.195$, $R2 = 0.1791$) ball speed. Thus, based on these preliminary results, it seems that within-individual elbow load variability is not related to performance in this group of pitchers. In practical terms, this means that a pitcher should strive to minimize their elbow load variability as it might reduce the chance of sustaining an injury without influencing performance. It is known that a “proper” technique is related to the elbow valgus torque [7], and thus it might also be related to the load variability. For injury prevention, it should be investigated whether a pitcher is able to minimize their elbow load variability consciously.

The study population was a homogenous group of youth elite baseball pitchers (age 15–22). It is known that the magnitude of external elbow valgus torque increases with the level of play [11]. The group average valgus torque variability did not show significant differences between levels of play according to Fleisig et al. (2009) [26], indicating that our results showing differences between pitchers in within-individual load variability can be extended to other levels of play. A large difference between our study and the study of Fleisig et al. (2009) is that they only included the 5 fastest pitches in their analysis to describe within-individual variability, which is less compared to the 25 analyzed pitches in our study. Five pitches are too few to define whether the valgus torque is normally distributed. Therefore, it is unclear whether the finding that a load distribution can be described with a Gaussian distribution can be extended to other levels of play.

A limitation of this study is that the external valgus torque magnitude and variability are assumed to be representative of the magnitude and variability of the UCL load. The literature shows that, in addition to the UCL, elbow muscles and joint articulation can also counteract the external valgus torque [27]. How the magnitude and variability of the valgus torque load are distributed over these anatomical structures is yet unknown. Thus, how much of the valgus torque magnitude and variability can be translated to the UCL load and variability should be investigated in the future. In conclusion, as it is known that the external valgus torque is related to UCL load and UCL injuries [14,28], we conclude that UCL load variability is present within baseball pitchers. However, the exact values of magnitude and variability depend on other elbow stabilizers and the individual pitcher.

CONCLUSION

In conclusion, this study showed that within-individual elbow load variability is present in youth elite baseball pitchers and that the within-individual load variability differs between pitchers. It is possible to describe the elbow load distribution with a Gaussian distribution, in which the standard deviation describes the within-individual load variability. Therefore, in addition to the load magnitude, the within-individual load variability seems important in injury assessment and possibly in injury prevention. To make it relevant to injury prevention, future research should investigate whether load variability changes over time and whether it can be minimized by pitchers.

Data availability

The data underlying this study can be found here: DOI 10.3390/app12136549

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APPENDIX

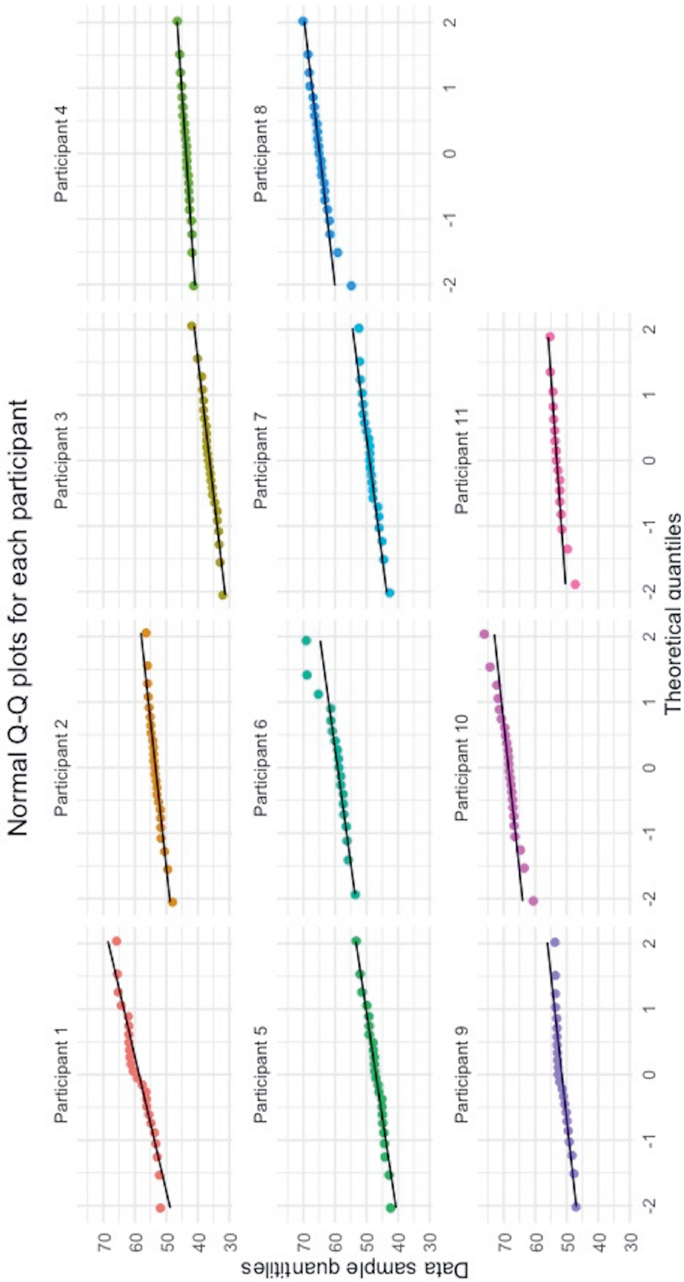

Figure A.1. This figure shows the Q-Q plots for the external valgus torque for each participant.

5

CHAPTER 6

Magnitude and variability of individual elbow load in repetitive baseball pitching

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ABSTRACT

In baseball pitchers the elbow is exposed to high and repetitive loads (i.e. external valgus torque), caused by pitching a high number of balls in a practice session or game. This can result in overuse injuries like the Ulnar Collateral Ligament (UCL) injury. To understand injury mechanisms, the effect of repetitive pitching on the elbow load magnitude and variability was investigated. In addition, we explored whether repetitive pitching affects elbow muscle activation during pitching. Fifteen pitchers threw each 60 to 110 balls. The external valgus torque and electromyography of three elbow muscles were quantified during each pitch. Linear mixed model analyses were performed to investigate the effect of repetitive pitching. On a group level, the linear mixed models showed no significant associations of repetitive pitching with valgus torque magnitude and variability and elbow muscle activity. Significant differences exist between pitchers in their individual trajectories in elbow valgus torque and muscle activity with repetitive pitching. This shows the importance of individuality in relation to repetitive pitching. In order to achieve effective elbow injury prevention in baseball pitching, individual characteristics of changes in elbow load and muscle activity in relation to the development of UCL injuries should be investigated.

INTRODUCTION

High performance in physical sports is closely related to musculoskeletal injuries. In baseball pitching, for instance, an important performance outcome is ball speed. For high performance, i.e. a high ball speed, a fast full-body motion is required, which exposes the musculoskeletal system to high mechanical load[1]. More specifically, in baseball pitching, the elbow is exposed to significant loads that might result in (overuse) elbow injuries. Most injuries at the elbow are on the medial side [2], and more specifically on the ulnar collateral ligament (UCL). UCL injury rates in baseball pitching at all levels of play have gradually increased over the years [3,4], as has surgery as a treatment option that involves reconstructing the UCL [5], also known as the Tommy John surgery. To prevent injuries and the need for surgery among pitchers, it is crucial to understand the mechanisms of injury. This understanding can aid in the development of effective preventive measures.

Biomechanics could help to understand the injury mechanisms. It is stated that overuse injuries result from repetitive loading and cumulative bouts of activity and its interaction, defined as the mechanical fatigue phenomenon [6]. In terms of UCL injuries in baseball pitching, it is thus important to quantify the cumulative activity and the exposure to UCL load, preferably in terms of frequency, magnitude, and duration. Pitch count is an easy way to quantify the frequency and studies have shown that it is related to UCL injuries[7,8]. However, mechanical fatigue tests have shown that the risk of overuse injuries increases substantially with loading magnitude rather than loading cycles (i.e. frequency)[6]. The external valgus torque is frequently used as a proxy for UCL loading, as it is known that the UCL at least partially resists this torque [9–11]. Hence, a good measurement for the magnitude in baseball pitching is the external valgus torque. Thus, in baseball pitching, the pitch count and valgus torque, and its interaction seem important in relation to UCL injuries.

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The external valgus torque around the elbow is generated by a rotational inertia component: a resistance to angular accelerations, and a translational inertia component: a resistance to linear accelerations[12]. The magnitude of the valgus torque depends on the position of the arm as well as the accelerations and is thus influenced by adjustments in pitching technique. Biomechanical changes and thus alteration in the external valgus torque might be related to changes in pitching technique because of a high number of balls in a practice session or during a match (i.e. repetitive pitching).

Three studies investigated the effect of repetitive pitching on the external valgus torque magnitude for different levels of play[13–15]. Darke et al. (2018) reported that the external valgus torque did not significantly change after throwing 75 balls in youth baseball pitchers [13]. Escamilla et al. (2007), who compared the external valgus torque between the last and the first inning of a simulated game, with an average of nine fastballs within each inning, also found no significant difference at the group level among collegiate pitchers. Murray et al.

(2001) compared the valgus torque during a single pitch of the first inning with one from the last inning in professional baseball pitchers [15], and also did not find significant differences on a group level.

Recently, we showed that within-individual load magnitude and variability differ among pitchers and that especially this variability might be related to overuse injuries [16]. A higher within-individual load variability increases the risk of sustaining an injury as, while the average load remains equal, more extreme values, closer to or even over the acute overuse injury level are likely to occur. Therefore, it is preferential to include multiple pitches in the analysis of an individual to investigate the effect of repetitive pitching on the elbow valgus torque magnitude and variability.

While investigating the association between repetitive pitching and UCL injuries with the external elbow valgus torque as elbow load measure, it should be noticed that the UCL is not the only structure that resists the external valgus torque. The elbow muscles can directly, via the flexor-pronator muscle group (FPM), and indirectly, via the co-contraction of the biceps and triceps muscles in relation to the joint geometry, counteract the elbow valgus torque [9,10]. The valgus torque is thus distributed over these structures, where the muscles might shield the UCL from high loads. In a previous study, we reported FPM activity at maximal external shoulder rotation, the critical moment when the peak external valgus torque occurs [17]. In addition, the biceps and triceps muscles were shown to be active at this critical moment [17]. A change in the muscle activation at the moment of the peak external valgus torque, due to for example a late onset or reduced muscle activity, could increase the UCL load while the external valgus torque remains the same. A prediction model by Sonne & Keir (2016) demonstrated that significantly more FPM muscle fatigue existed when the time between adjacent pitches was shorter. (8 seconds compared to 20 seconds) [18], but possible changes in muscle activation in relation to repetitive pitching have not yet been subject of study.

The aim of this study is to determine whether there is a change in within-individual load magnitude and variability as an effect of repetitive pitching due to musculoskeletal fatigue-related kinematic changes during pitching. Based on the current literature it is expected that elbow valgus torque magnitude will not change with repetitive pitching, whereas the relationship of variability with repetitive pitching is difficult to predict. In addition, we intend to determine if and how repetitive pitching affects the activation of the FPM, biceps, and triceps during pitching.

METHODS

Participants

Data were collected from fifteen healthy male baseball pitchers. Mean age was 24.5 years (SD 7.5), body height 191 cm (SD 5), body mass 79.4 kg (SD 9.2), and average ball speed 67mph (SD 4). Of the fifteen tested pitchers, 11 were right-handed. Most participants were pitching at a recreational level, with two participants playing at the highest level and one pitcher at the second highest level in the Netherlands. Specific individual information can be found in Table1. None of the participants had experienced any musculoskeletal injuries in the past six months nor had they received elbow surgery in the past. The study protocol followed the guidelines stated in the Declaration of Helsinki [19] and was approved by the Ethics Committee of the Delft University of Technology (HREC). Participants were informed of the procedure before the start of the measurements. Informed consent was obtained before involvement in the study.

Table 1 shows characteristics of each participant. Age is in years. The level in the Netherlands range from low to high in the order of 6th recreational level, 4th recreational level, 3rd recreational level, 2nd recreational level, 1st recreational level, 2nd professional baseball league, highest professional baseball league. Pitching experience is in years. Body length is in meters and body weight is in kilograms. The average ball speed is in mph.

Participant Number	Age	Level	Pitching experience	Type of pitcher	Body length	Body weight	Average ball speed
1	22	4th recreational level	10	Reliever	1.89	73.4	66
2	19	Highest professional league	11	Starter	1.93	85.9	74
3	25	4th recreational level	5	Starter	1.96	88.9	65
4	29	3rd recreational level	20	Reliever	1.91	78.5	67
5	44	6th recreational level	32	Starter	1.99	102.5	62
6	24	4th recreational level	12	Starter	1.85	71.0	68
7	18	1st recreational level	5	Reliever	1.91	75.9	70
8	17	1st recreational level	4	Starter	1.83	62.7	66
9	23	Highest professional league	5	Reliever	1.97	85.0	75
10	21	1st recreational level	12	Reliever	1.89	78.1	61
11	37	2nd recreational level	26	Starter	1.85	82.2	66
12	26	2nd recreational level	12	Starter	1.94	74.8	63
13	17	2nd professional league	5	Starter	1.92	81.9	73
14	24	4th recreational level	6	Starter	1.88	75.5	62
15	20	2nd recreational level	7	Starter	1.99	74.3	69

6

Procedure

The measurements were performed at the indoor human movement laboratory of the Department of Human Movement Sciences at the Vrije Universiteit Amsterdam, The Netherlands. Fourteen reflective markers were placed on anatomical bony landmarks of the participants with double-sided tape. Electromyography (EMG) electrodes were placed on the skin of the throwing arm and an accelerometer was attached to the sternum below the incisura jugularis. The participants wore their own shoes, athletic shorts, and baseball glove, but no shirt. Prior to performing fastball pitches, participants had to perform maximum voluntary contractions for each muscle separately (MVC, see Chapter 3 supplementary materials). Participants gradually built-up muscle force and held this for 3 seconds. Each MVC was repeated three times. After performing their regular warm-up, the participants were instructed to pitch fastballs at full effort. Ten fastball pitches were performed within a block of pitches, with two minutes rest between each block. Before the start and between 10 blocks of pitches, the participants were asked about their self-perceived fatigue with the following text: "Place a vertical line on the visual analog scale shown below in which way you are overall fatigued". The visual analog scale (VAS) ranged from totally not fatigued (0%) to extremely fatigued as possible (100%). Participants were instructed to stop when having thrown 110 fastballs or when their VAS score reached 80%. The minimum required number of pitches was 60. To investigate the effect of fatigue on variability, all the pitches were measured and included in the analyses. Participants pitched from a pitching mound (height 0.55m) towards a strike zone (height 0.71m; width 0.43m), at 18.66 m.

Data acquisition

Kinematics and ball speed

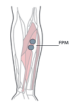
Marker positions were recorded using an OptiTrack motion capture system with twelve cameras sampling at 120 Hz (OptiTrack Flex 13, OptiTrack™, Corvalis, United States). The OptiTrack system was calibrated to define camera position and orientation and to construct a convenient global coordinate system. The ball speed was measured behind the strike zone using a stalker pro radar gun (Stalker Radar, Plano, TX, USA).

Electromyography

Muscle activity of three elbow skeletal muscles of the throwing arm was measured using bipolar surface electromyography (sEMG). The flexor pronator mass (FPM), biceps brachii (BIC), and triceps brachii (TRI) muscles were measured (Table 2). The electrode locations were based on the SENIAM guidelines (Hermens et al. 1999). The reference electrode was placed on the clavicle of the non-throwing arm. Disposable bipolar electrodes (Ag-AgCl; 1 cm^2 recording area; Blue Sensor Electrodes N-00-S, Ambu Inc., USA) were attached in the direction of the muscle fibers with 2 cm distance between the centers of the electrodes.

Before the electrodes were attached, the skin was shaved and cleaned using alcohol. The electrode cables were fixated to the skin to avoid cable movement artifacts in the signal and to minimize the risk of loosening of the electrodes from the skin during pitch movement. The cables were connected to a BioPlux research device (Plux biosignals, Lisboa, Portugal), with 16-bits analog channels, a gain of 506, and an analog 25-500Hz band-pass filter. All consecutive fastball pitches of a participant were recorded in one EMG dataset at a sampling frequency of 2000Hz and locally stored on the BioPlux research device.

Table 2. Electromyography electrode position and orientation.

Muscle (group)	Electrode position and orientation	Electrode placement
m. biceps brachii (Bic)	On the line between the medial acromion and the fossa cubit at 1/3 proximal from the fossa cubit.	
Flexor Pronator Mass (FPM)	At 1/3 distal from the medial epicondyle. In the direction of the line between the medial epicondyle and the middle of the radial and ulna styloid	
m. triceps brachii (Tri) (lateral head)	At 1/2 on the line between the posterior crista of the acromion and the olecranon at 2 finger widths lateral to the line.	

Data analysis

All data analyses were performed in Python (version 3.7, Python Software Foundation, https://www.python.org/).

Kinematics and inverse dynamics

The following bony landmarks on the throwing arm were used to construct an anatomical local coordinate system for the hand, forearm, and upper arm according to the ISB recommendations [20]: third proximal interphalangeal, ulna processes styloid, radius processes styloid, lateral humeral epicondyle, medial humeral epicondyle, and the acromion. Positions of the centers of mass and the moments of inertia were estimated according to Zatsiorsky (2002)[21] and De Leva et al. (1996)[22]. The elbow joint angles were decomposed in the rotation order of 'flexion/extension' – 'ab/adduction' (floating angle)- 'pronation-supination' according to Grood and Sunday (1983). The shoulder angle was defined as the humerus in relation to the thorax. Maximal external shoulder rotation (MER) was obtained from the shoulder joint angles decomposed according to the y-x-y Euler decomposition ('plane of elevation'-'negative elevation'-'axial rotation') [23].

The net joint forces and moments were calculated in the global coordinate system, using a top-down inverse dynamics analysis based on the Newton-Euler equation of motions. Subsequently, the elbow joint torque was expressed in the anatomical coordinate system of the elbow; positioned in the middle of the medial and lateral humeral epicondyles. The kinetics of the segments were calculated with the segment data and scaling factors of De Leva et al. (1996) and Zatsiorsky et al. (1990). A 2nd order polynomial function was fitted using five measured data points to obtain the exact magnitude of the peak value of the external valgus torque, which occurred around the moment of MER. The inverse dynamical model can be found here: https://github.com/ThomasBTHL/BTHL_public.

Electromyography

EMG signals were first separated into the ten-pitch series. Subsequently, these were cut into single pitches. The linear envelope was obtained by rectifying the EMG and applying a fourth-order bi-directional lowpass Butterworth filter of 20Hz. EMG data were normalized to the maximum values observed in the MVC data. To quantify the indirect effect of the biceps and triceps muscles, a co-contraction index (CCI) was calculated for the biceps and triceps muscle pair at each sample (i) according to Rudolph et al. (2000)[24], see equation (1).

$$CCI_i = \frac{EMG_{low,i}}{EMG_{high,i}} * \left(EMG_{low,i} + EMG_{high,i}\right) \qquad \text{(Equation 1)}$$

An area under the curve (AUC) was calculated over a window of 150ms for the normalized EMG data and the CCI. This window was chosen because the time between the events of foot contact to ball release is approximately 150ms[25], and includes the moment of the peak valgus torque. To represent the muscle activity as an indication of the timing of relative muscle force, the normalized EMG data was compensated with 50ms for the electromechanical delay (EMD)[26]. The moment from maximal external rotation to ball release is approximately 50ms[17], which is similar to the EMD. Therefore, the AUC window started at MER at 0ms and ranged back to -150ms to represent the timing of relative muscle force from foot contact to ball release.

Synchronization

The BioPlux device, containing the EMG signals and accelerometer data, did not contain the MER event. Therefore, it was synchronized with the OptiTrack system. The z-direction of the accelerometer, pointing forwards relative to the thorax, was synchronized with the forward acceleration of the trunk coordinate system. For each pitch, the data were synced on the peak linear accelerations and stored in a Python pickle.

Moving window approach

In addition to ball speed, four outcome variables were analyzed in relation to repetitive pitching: the elbow valgus torque magnitude, valgus torque variability, the FPM AUC, and the biceps-triceps CCI. A moving window of ten pitches was applied to all variables and moved over a single subsequent pitch. The mean of the ten values within each window was used to quantify the trajectory of ball speed and the valgus torque magnitude, and the standard deviation of the ten values within each window was used to quantify the trajectory of the within-individual valgus torque variability over the individual sessions of 60-110 pitches (see Figure 1). For the EMG outcome variables, the means of the ten values of the moving 10-pitch windows were quantified as the FPM activity and the biceps-triceps CCI.

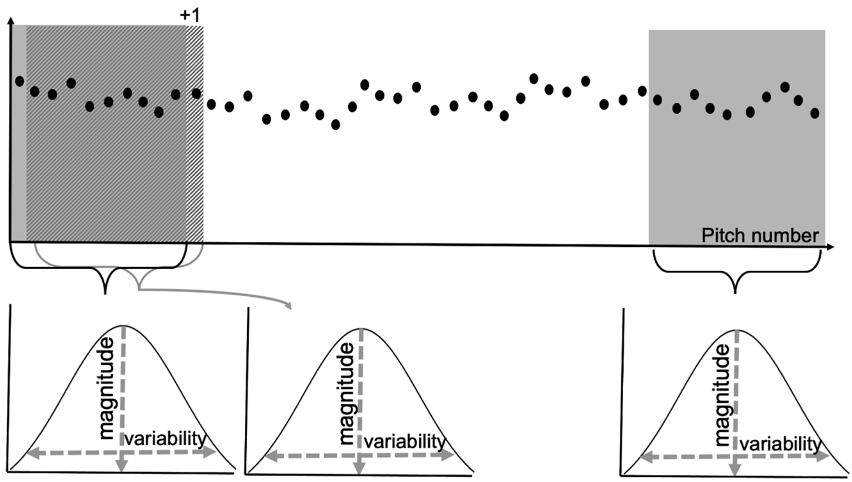


Figure 1. Visualization of the ten-pitch moving window approach moving over a single subsequent pitch.

Statistical analysis

To statistically explore the relationship between ball speed and the four outcome variables and repetitive pitching five linear mixed models (LMM) were examined. The LMM deals with missing data and data of different samples [27], which is an advantage as some participants indicated to be fatigued >80% after 60 balls, whereas others did not reach this level of fatigue after 110 balls. The fixed factor was the number of subsequent moving windows for each individual series of pitches and the random factor was the participant. Given the multilevel structure of the data (level 1 pitch window number nested in level 2 participants), it was considered necessary to build three models: (1) a basic model with a random intercept across participants, (2) a model with pitch window number as a predictor and random intercept across participants and (3) a model with pitch window number as a predictor, a random effect of pitch window number over participants (random slope) and random intercepts. To select the best-fitted model, the models were compared using a chi-square likelihood ratio test with a significant level of 0.05. If the models were significantly different, the model with the smallest AIC value was used. The maximum likelihood was used as the estimation method. The nlme package for R was used to perform the LMM analysis [28]. All statistical analyses were performed in R (version 4.2.0) [29] and Rstudio (version 2022.2.0.443) [30].

RESULTS

After visually inspection of the signals, for instance, due to missing markers, 951 pitches from 14 pitchers were included in the analysis. Participant 2 was removed because only thirteen pitches of the in total 60 pitches could be analyzed after preprocessing, which is not representative of repetitive pitching. Participant 1 did not have EMG data and was therefore not included in the EMG analyses.

Ball speed

Ball speed was not significantly associated with window (or pitch) number *(*p = 0.76), indicating that ball speed remained constant throughout the pitching sessions of 60-110 throws. The visualization of these results can be found in supplementary materials.

Magnitude and variability in relation to repetitive pitching

The external valgus torque magnitude did not significantly change the fixed effect of pitch window number, and neither did the variability (Table 3). For both variables, the likelihood test showed that the linear mixed model with a random intercept and random slope was significantly the best model (Table 3, supplementary material). Figure 2A shows the results of the model with across participants the significant random intercept (SD 8.71; 95% CI: 6.01 12.61) and the significant random slope (SD 0.044; 95%CI 0.030, 0.064) for the external valgus torque magnitude. The linear mixed model of external valgus torque variability shows significant variance across participants for the random intercept (SD = 0.64; 95% CI: 0.43, 0.94) and the random slopes (SD = 0.01; 95%CI: 0.006, 0.015) (Figure 2B). The standard deviation across participants for the slope was larger compared to pitch window number as a fixed effect, in both the magnitude and within-individual variability model. The likelihood test and the significant slope variances across participants indicate that the external valgus torque magnitude and variability depend on the individuals in relation to pitch window number.

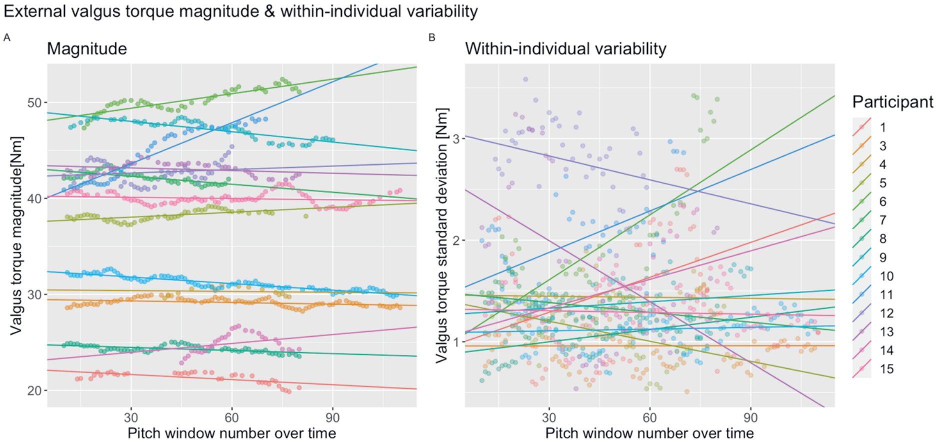


Figure 2. Panel A shows the relationship with the magnitude of the external valgus torque in relation to pitch number. Panel B shows the variability in relation to pitch number. Each colored line represents the modeled LMM intercept and slope of a participant.

*Table 3. shows the results of the linear mixed model analysis of the predictor variable window number in association with the four outcome variables. ß is the slope of the linear relationship of the fixed effect. CI is the confidence interval with the lower and upper limits at respectively 2.5% and 97.5%. * p<0.05.*

	ß	CI		t	significance
Valgus torque					
Magnitude	0.0083	-0.0148	0.0314	0.70	0.482
Variability	0.0017	-0.0039	0.0073	0.59	0.553
EMG					
FPM (AUC)	$-1.9*10^{-4}$	$-5.0*10^{-4}$	$1.1*10^{-4}$	-1.22	0.223
CCI Triceps-Biceps	$-1.8*10^{-4}$	$-3.6*10^{-4}$	$6.6*10^{-6}$	-1.89	0.059

Elbow muscle activity in relation to repetitive pitching

The FPM, biceps brachii and triceps brachii muscles showed activity in all participants during pitching. The FPM AUC activity was not significantly associated with the fixed effect of pitch number (Table 3). The underlying best-fitted model was the model with a random intercept and random slope across participants. Figure 3A shows the significant variance in intercepts across participants (SD = 0.06; 95% CI: 0.04, 0.09), and the significant random slopes (SD = 0.0008; 95% CI: 0.0005, 0.0012).

The biceps-triceps CCI showed a negative trend with pitch window number but was not significant (Table 3). Again, the best-fitted model was the model including random intercept and random slope. The intercept (SD = 0.04; 95% CI: 0.027, 0.059) and slope (SD = 0.0003; 95% CI: 0.0002,0.0005) varied significantly across the participants (Figure 3B).

These results indicate that on a group level repetitive pitching is not associated with FPM AUC activity and biceps-triceps CCI. The significant random slope difference across participants indicates that pitchers show a different FPM muscle activity and biceps-triceps CCI between each other in relation to pitch window number.

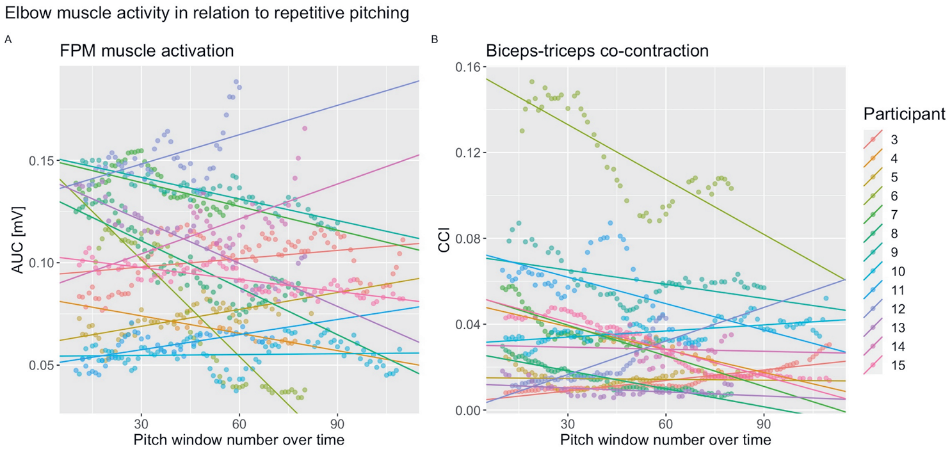


Figure 3. Panel A shows the relationship between the FPM activity area under the curve (AUC) with pitch window number. Panel B shows the biceps-triceps CCI in relation to the pitch window number. Each colored line represents the modeled LMM intercept and slope of a participant.

DISCUSSION

The aim of this study was to investigate if repetitive pitching influences the peak external valgus torque magnitude and variability during pitching, and to investigate the relationship between repetitive pitching and elbow muscle activation during pitching. The results showed no significant relationship between the external valgus torque magnitude and within-individual variability with repetitive pitching on a group level; but both variables showed significant variance in the association across participants. On a group level, the FPM activity was not significantly related to repetitive pitching. In addition, the biceps-triceps co-contraction index showed a trend but was not significant in relation to repetitive pitching. The FPM activity and the biceps-triceps co-contraction index showed significant variance in the association across participants. Thus, it is important to consider the individual differences for both the external valgus torque and elbow muscle activations in relation to repetitive pitching.

The external valgus torque in combination with pitch number is important in relation to UCL injuries, an higher external valgus torque with an increase in pitch number raises the chance of sustaining a UCL injury. Previous studies did not find an effect of repetitive pitching on the valgus torque by comparing the first and the last inning [13,14]. This is in line with our results, as no significant effect on group level was found between repetitive pitching and elbow valgus torque magnitude and variability, except that our results revealed that the individual association with repetitive pitching is very different across participants. The different responses across participants are an important finding as these can explain why no relationship with repetitive pitching was found on a group level. The importance of individuality has been shown earlier as the valgus torque magnitude and within-individual variability show considerable differences between pitchers in elbow load magnitude [31,32] and in the load variability [16]. The results of the current study revealed also that individual differences are important in the association between elbow load and repetitive pitching.

The individual association of elbow load magnitude and within-individual variability with repetitive pitching emphasizes the importance of an individual approach in relation to the quantification of load and overload. This individual approach seems essential in relation to overuse injuries because it is hypothesized that pitchers who have a higher load magnitude and within-individual variability are at higher risk for sustaining an injury [33]. This, in combination with the mechanical fatigue phenomenon, where an increase in loading cycles (pitch count) and loading magnitude (valgus torque) increases the chance of damage, are important factors in overuse injuries. In terms of injury assessment, this knowledge is part of the larger complex puzzle to explain why one pitcher sustains an injury and another does not.

For injury prevention, the next step is to understand why one pitcher shows an increase and another a decrease or no changes in within-individual load magnitude and variability when performing relatively long sessions of repetitive pitching. Biomechanical variables earlier in the kinetic chain (such as leading leg knee extension and trailing leg knee flexion, and an earlier trunk rotation) are associated with an increased external valgus torque [34,35]. Alterations within an individual in these variables and other proximal intersegmental interactions could increase the external valgus torque magnitude and variability during repetitive pitching. In terms of injury prevention, it is thus important to investigate if these biomechanical variables can be trained to maintain a constant elbow load during repetitive pitching.

The FPM and the biceps-triceps CCI were active in all pitchers, with large inter-individual differences. It is difficult to explain the increase or decrease in muscle activation in pitchers. As a result of repetitive pitching, the AUC decrease in the subset of ten of our pitchers might reflect that they were not able to recruit the same amount of muscle fibers over the full duration of the experiment. On the other hand, pitchers who showed an increase might not have recruited all their muscle fibers in the beginning and compensate by an increase in muscle activation in association with repetitive pitching. The decrease could be especially dangerous, as it is known that pitchers with UCL insufficiency showed less activity in flexor carpi radialis and triceps muscles compared to uninjured pitchers [36]. Hence, several studies found a decrease in static grip force after repetitive pitching [37,38], indicating an effect of repetitive pitching on the FPM strength. To conclude, the decrease in muscle activity and co-contraction index could be related to a reduction of produced muscle force. On the other hand, increased muscle activity could indicate the recruitment of additional muscle fibers, acting as a compensation mechanism. Electromyography is a noisy signal, and the results should thus be interpreted with caution, the next step is to investigate if the individual decrease in FPM activity and co-contraction levels are related to a decrease in muscle strength.

In baseball games, pitchers throw multiple pitch types such as breaking balls and fastballs. One limitation of this study is that the pitchers were instructed to throw fastballs only, because we were interested in the effect of repetitive pitching on the within-individual magnitude and variability of the elbow load and not in the differences between pitch types. Throwing a breaking ball produces less valgus torque [32]. Thus, the inclusion of other pitch types will show more variance in external valgus torque magnitude and variability. A lower valgus torque does not per definition imply a lower UCL load, because if the muscle force is decreased the UCL resists more stress. During breaking balls lower elbow muscle activations are reported [39], assuming that the muscle force is also lower, which suggests that the shielding effect is different and might be even lower, in breaking balls compared to fastballs. A more in-depth comparison of muscular activity in different pitch types is therefore necessary.

The number of participants (n=15) included in this study is comparable to other simulated game studies [14,40]. However, it is a relatively small sample size and therefore a limitation of this study. This is primarily due to the difficulty in recruiting pitchers to perform a fatiguing study, as such a number of pitches disrupt their training regime. In addition, in this study, the aim was to investigate the effect of repetitive pitching on the within-individual elbow load. Therefore, in comparison with other studies, we focused on analyzing many throws of individual pitchers, resulting in an enriched within-individual dataset. Another limitation is that the training load of the pitchers was not reported. This might have influenced the results as the study population was heterogeneous including recreational pitchers and professional pitchers. Overall, professional pitchers are exposed more frequently to higher loads and have better facilities and training schedules compared to recreational pitchers. This might have influenced the trajectory of muscle recruitment in relation to repetitive pitching. Future studies should investigate if training status and level of play influence the effect of repetitive pitching on muscle recruitment.

In this study, we investigated the association between repetitive pitching and elbow load during a single session. An injury can occur during only one single pitch when the peak load is higher than the UCL load capacity. However, most of the time it is a result of repetitive motion as the overall injury rate in baseball is 3.6 per 1000 athletes-exposures, with the elbow as the most injured part [41]. To prevent pitchers from injuries, monitoring the within pitcher development of the elbow load magnitude and frequency during every athlete's exposure over multiple seasons is important. Wearables, like inertial measurement units (IMUs) can be used by individuals in the field to predict the elbow load [42]. Pitch count can be used as a substitute for loading frequency, while external valgus torque can be utilized to quantify the elbow load magnitude. Many studies used the external valgus torque to quantify the medial elbow load and used this as a proxy for UCL load [40,43]. However, as seen in this study, to quantify the UCL load it is important to consider the protection mechanism of the elbow muscles, especially individually in relation to repetitive pitching. Quantifying muscular activity with electromyography in a daily training session is upcoming but not yet possible. To mitigate pitching injuries in the future, a warning system can be developed based on monitoring the elbow load magnitude and frequency, and muscle activity. Future research in the field of UCL injuries should quantify the within-individual elbow load magnitude and variability over time.

CONCLUSION

Repetitive pitching shows significant differences among pitchers in the relationship with the elbow within-individual load magnitude and variability, FPM activity, and the biceps-triceps co-contraction. The variation among pitchers could explain why no significant relationship was found on a group level. The differences in muscle activation among pitchers in relation to repetitive pitching show that the shielding effect of elbow muscles should be included when quantifying the UCL load and cannot be considered a constant variable. In the field of UCL injury assessment and especially injury prevention, our results show that it is important to measure the within-individual UCL load magnitude and variability in relation to repetitive pitching because these metrics could be part of the puzzle of understanding why one sustains an injury and another not. Future studies should investigate why some pitchers showed an increase in elbow within-individual load magnitude and variability load and others a decrease in relation to repetitive pitching and subsequently how it is causally related to UCL injuries.

Data availability statement

The datasets generated and analyzed in this study are available via DOI: 10.4121/22093103.

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APPENDIX

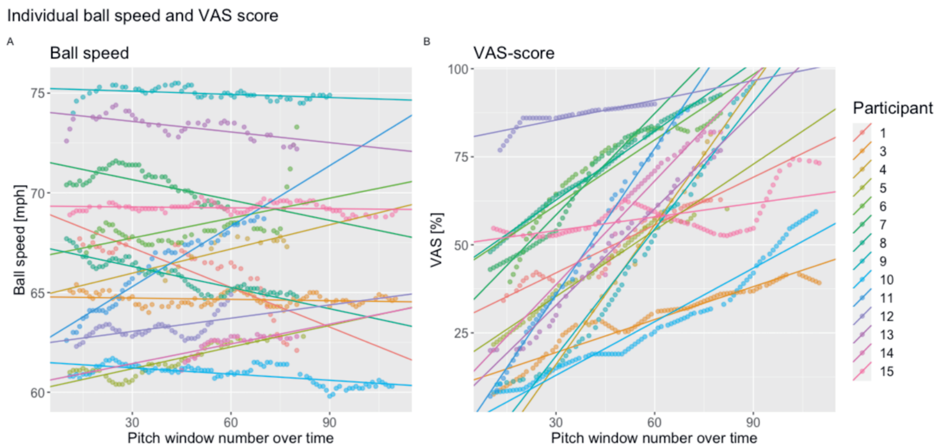

Figure 1. Panel A shows the relationship with the ball speed in relation to pitch window number. Panel B shows the VAS-score in relation to pitch window number. Each colored line represents the modeled LMM intercept and slope of a participant.

Table 1. Loglikelihood results between the three different models for the four outcome variables. Model 1 was a basic model with a random intercept across participants. Model 2 included the pitch window number as predictor and random intercept across participants. Model 3 included pitch window number as predictor, a random effect of pitch window number over participants (random slope) and random intercepts.

	model 1 vs model 2	**model 2 vs model 3**
Valgus torque magnitude	$\chi2(1) = 2.47$, $p = 0.115$	$\chi2(2) = 703.7$, $p < .001$
Valgus torque variability	$\chi2(1) = 3.79$, $p = 0.054$	$\chi2(2) = 139.8$, $p < .001$
FPM AUC	$\chi2(1) = 63.84$, $p < 0.001$	$\chi2(2) = 614.7$, $p < .001$
Biceps-Triceps CCI	$\chi2(1) = 64.8$, $p < 0.001$	$\chi2(2) = 521.8$, $p < .001$

CHAPTER 7

The Ulnar Collateral Ligament response to valgus stress, repetitive pitching, and elbow muscle contraction in asymptomatic baseball pitchers

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ABSTRACT

Background

In baseball, repetitive pitching leads to medial elbow injuries, particularly to the ulnar collateral ligament (UCL). To prevent pitchers from UCL injuries, it is important to quantify the response to elbow stress. Repetitive elbow external valgus torque and muscular fatigue induced by repetitive pitching could affect markers of the response, i.e. humeroulnar joint gap and UCL morphology. The aims of the study were three folded; to investigate the effect of (1) exerted handgrip force on the humeroulnar joint gap (2) repetitive pitching on the humeroulnar joint gap and the UCL morphology, and (3) exerted handgrip force on the humeroulnar joint gap for different levels of elbow valgus stress is different after compared to before repetitive pitching in asymptomatic baseball pitchers.

Methods

Medial elbow ultrasound images were collected in 15 asymptomatic male baseball pitchers. Three levels of static elbow valgus stress (0N, 50N, 100N) were applied with a TELOS device, before and after repetitive pitching and with or without handgrip force. These images were used to assess the humeroulnar joint gap size and UCL length and thickness. After 110 fastball pitches or when 80% self-perceived fatigue on a VAS scale was reached, participants were instructed to stop throwing. Repeated measures ANOVAs were used to statistically test significant differences.

Results

Handgrip force did not significantly affect the humeroulnar joint gap. The UCL thickness and length and the humeroulnar joint gap were also not different after compared to before repetitive pitching. While higher levels of applied valgus stress significantly increased the humeroulnar joint gap ($p<0.001$), this effect was not significantly different in the interaction with handgrip force and repetitive pitching.

Conclusion

Although the humeroulnar joint gap changes for different levels of elbow valgus stress, handgrip force and repetitive pitching, however, did not affect the humeroulnar joint gap or the UCL morphology in baseball pitchers within a pitching session.

INTRODUCTION

In baseball, pitchers may experience discomfort or pain during the baseball season while continuing to play. This frequently results in injuries to the musculoskeletal system. In Major League Baseball pitchers, around 28% of player disabilities were due to elbow injuries [1] resulting in losses of 1.9 to 3.9 million dollars per player [3]. The most common surgery in the treatment of elbow injuries is the Tommy John surgery, which is performed to recover the function of the insufficient ulnar collateral ligament (UCL). In professional baseball, 25% of the Major League Baseball pitchers and 15% of the Minor League Baseball pitchers have a history of such a surgery [4].

It is not surprising that pitching in baseball is associated with a high incidence of elbow injuries and surgeries. Pitching exerts great forces on the human body and in particular on the medial structures of the elbow [5]. In the late cocking or early acceleration phase of the pitch, the shoulder is positioned at maximal external rotation. In combination with accelerations, angular velocities, and inertia in the performance of the pitch this results in an external elbow valgus torque [6]. During pitching, peak external valgus torques around 50Nm are reported [7,8]. This peak torque stresses the medial side of the elbow and produces a compressive force on the lateral side. This external valgus torque is resisted by the UCL as a structural stabilizer and elbow muscles as functional stabilizers [9]. The interaction between the structural and functional stabilizers and the joint geometry counteracts the external valgus torque [9]. Thus, in the evaluation of the medial elbow load, i.e. the external valgus torque, in baseball pitching it is, in addition to the frequently treated UCL, important to consider the influence of elbow muscles.

Hattori et al. (2020) investigated the effect of elbow muscles on the humeroulnar joint gap by exerting handgrip force while measuring the joint gap. While participants were in a supine position and only gravity induced a valgus stress on the medial side of the elbow, exerting maximal handgrip force decreased the humeroulnar joint gap [10]. This indicated a stabilizing effect of the forearm flexor and pronator muscles on the elbow joint. During pitching the elbow is exposed to much higher elbow valgus torques compared to those caused by gravity in the experiment of Hattori et al. (2020). However, it is unknown whether the elbow muscles, while being active because of gripping, can counteract the valgus torque under higher levels of valgus stress, and thus shield the UCL from high stresses.

In the study of Hattori et al. (2020) ultrasound imaging was used to investigate the humeroulnar joint gap. When sustaining an overuse UCL injury, ultrasound images can show a change in morphology of the UCL, with complete tears of the UCL showing a ring-down artifact [11]. In addition, pitchers with a UCL tear show a greater humeroulnar joint gap with a manually applied static valgus stress in comparison to the humeroulnar joint gap of asymptomatic pitchers [12]. Ultrasound imaging, a non-invasive method, can thus be helpful in the study of the effects of repetitive pitching on structures of the medial elbow. Although it is yet not possible to measure the UCL morphology or the humeroulnar joint gap during baseball pitching, it is possible to measure the responses to elbow stress of repetitive pitching using static ultrasound imaging [13–15]. During seasonal load, the UCL responds to stress by becoming thicker and the humeroulnar joint gap increases, on the contrary, during off-season rest, the UCL becomes thinner and the humeroulnar joint gap decreases [15]. This shows that the UCL morphology, i.e. UCL thickness, adapts to seasonal changes in exposure to elbow stress. Whether changes in UCL morphology can also be observed directly after a single training session with repetitive pitching is unclear.

The humeroulnar joint gap in youth baseball pitchers significantly increased when pitching 60 balls, which became even more clearly visible after 100 pitches [16]. Although the authors concluded that this was likely due to muscle fatigue, they did not investigate the effect of handgrip force on the humeroulnar joint gap before and after repetitive pitching as indicator of elbow muscle fatigue. Investigating the effect of elbow muscle activity, by exerting handgrip force, on the humeroulnar joint gap before and after a repetitive pitching session could quantify the fatiguing effect of such a session on elbow muscles and the effectiveness of their potential shielding effect with respect to repetitive UCL loading. If at the same time, the fatigued elbow muscles are less capable of counteracting elbow valgus torque during pitching, this might result in within-session changes in UCL morphology, which together with the humeroulnar joint gap might be assessed using ultrasound imaging directly before and after a repetitive pitching session.

Therefore, the aims of this study were, first, to investigate the effect of the exertion of handgrip force on the humeroulnar joint gap for different levels of elbow valgus stress in asymptomatic baseball pitchers before pitching. Second, we aimed to investigate whether repetitive pitching affects UCL thickness and length and the humeroulnar joint gap for different levels of elbow valgus stress in asymptomatic baseball pitchers. The third and final aim of the present study was to investigate whether the effect of exerted handgrip force on the humeroulnar joint gap for different levels of elbow valgus is different after compared to before repetitive pitching in asymptomatic baseball pitchers.

METHODS

Participants

Fifteen asymptomatic male baseball pitchers participated in this study. Their mean age was 24.5 years (SD 7.5, range 17-44), body height 191 cm (SD 5, range 183-199) and body mass 79.4 kg (SD 9.2, range 62.7-102.5). Most participants were pitching at a recreational level, with two participants playing at the highest level in the Netherlands. They played baseball for an average of 15.5 years (SD 7.6) and had pitching experience of an average over 11.5 years (SD 8.4). None of the participants had experienced any musculoskeletal injuries in the past six months nor received elbow surgery in the past. There were 11 right-handed pitchers and 4 left-handed pitchers. Participants signed an informed consent form before the data were collected. Ethical approval was granted by the Human Research Ethics Committee (HREC) of the TU Delft on June 6, 2021.

Procedure

A controlled laboratory study was performed in which all participants underwent the same procedure. Three different levels of static elbow valgus stress, with and without handgrip force using a hand-held dynamometer, were applied using a TELOS device (Telos GA-IIE stress device; Telos, Weiterstadt, Germany). To investigate the humeroulnar joint gap and the UCL morphology, ultrasound imaging was used before and after pitching a minimum of 60 fastballs.

Before the first ultrasound measurement, the TELOS device was adjusted to the anthropometric characteristics of the participant (Figure 1). The device was adjusted to the participant's body height, while standing, with the upper arm at 90 degrees abduction, the elbow flexed at 30 degrees, and the forearm supinated to imitate the pitching posture near the posture of maximal external rotation at which the highest valgus stress levels are expected during pitching (Figure 1). To optimize the standardization of the ultrasound measurement with the participant in the TELOS device before and after a series of repetitive pitching, the orientation and position of the ultrasound probe were marked with a Sandel marker (Petite skin marker; Ansell; Iselin NJ; USA) on the skin of the participant's arm.

While being fixated in the TELOS device, the device was subsequently set at three elbow valgus stress conditions: 0 N, 50N, and 100N. For each of the valgus stress levels, ultrasound images of the medial part of the elbow were taken. Then, to measure the condition 'with grip force', participants were instructed to squeeze a hand-held dynamometer (JAMAR; Patterson Medical; Warrenville, IL, United States) to their maximum ability while being fixated in the TELOS device. From this reading, 20% was determined to be a pain-free and comfortable level. Again, with the participant in the TELOS device and exerting a handgrip force at 20% of their maximum effort, ultrasound images were collected at the imposed valgus stress levels of 0N, 50N and 100N. After this first sequence of collecting ultrasound images, the participant started his warm-up.

In the next part of the experiment, participants had to perform fastball pitches from a pitching mound towards a fictional strike zone (71*43 cm), at 18.66 meters. Ball speed was measured behind the strike zone using a radar gun (ACMI002; Applied concepts inc.; Plano, Texas, USA). The pitches were carried out in series of 10 pitches. Before the start and between these 10 pitches, participants were asked to indicate their level of self-perceived fatigue using a visual analog scale (VAS). The minimum required number of pitches for the experiment were 60 fastball pitches. Participants were instructed to stop pitching when throwing more than 110 fastballs or when their VAS score reached 80%. After the final pitch, the same sequence of collecting ultrasound images as before pitching was performed.

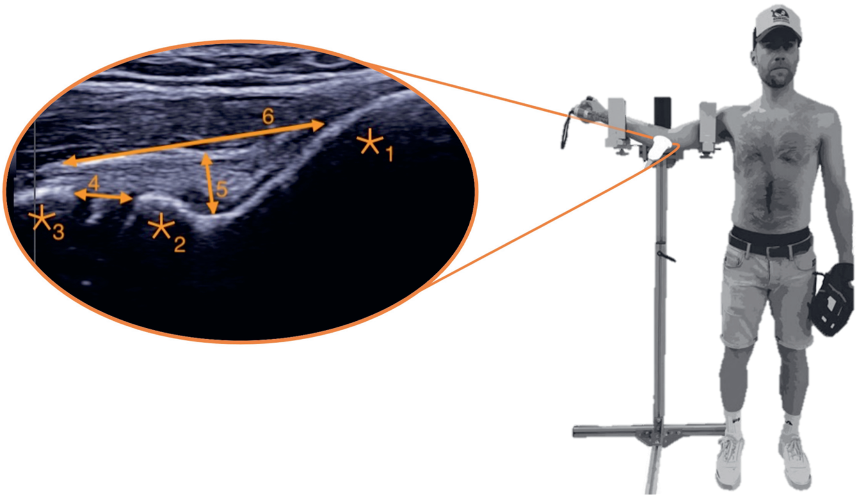

Figure 1. The right side of this figure shows the setup of the TELOS device on a self-build stand. The right-handed participant stands with the dynamometer in his hand. The ultrasound probe is positioned on the medial side of the elbow. The left figure shows the ultrasound image of the medial elbow, with 1. Medial epicondyle; 2. Humeral trochlea; 3. Sublime tubercle; 4. Humeroulnar joint gap; 5. UCL thickness; 6. UCL length.

Data collection

A Samsung ultrasound machine (HM70A; Samsung, Seoul, Republic of Korea) with a 12.3 MHz probe (LA3-16AD; Samsung, Seoul, Republic of Korea) was used to collect images of the medial side of the elbow. The ultrasound settings were set at 2.5 cm depth with a frequency of 12.3 MHz for optimal images (Figure 1). A total of 36 ultrasound images for each participant were collected, 18 before and 18 after pitching. The 18 images included the three conditions of elbow valgus stress (0N, 50N, 100N), with and without exerted handgrip force, and three images per condition. All ultrasound images were taken by one examinator (JvG), considering that the interobserver reliability was found to be sufficient for taking images of the anterior UCL with ultrasound [17]. After each ultrasound image, the examinator completely removed the ultrasound probe from the participant' elbow and repositioned the probe for the next image. Another investigator controlled the TELOS device to ensure proper elbow positioning for each condition.

Data analysis

All ultrasound images of the medial side of the elbow were analyzed separately by two investigators (BvT and JvG). To prevent the researchers from confirmation bias on the different conditions a randomizer script in Matlab was used to randomize all ultrasound images (Matlab 2019b; Mathworks, Inc.; Natrick, USA).

Figure 1 shows an ultrasound image of the medial side of the elbow. Bony landmarks, such as the medial epicondyle, the humeral trochlea, and the sublime tubercle were determined before drawing lines to determine the humeroulnar joint gap, the UCL thickness and the UCL length. ImageJ (ImageJ, U.S. National Institutes of Health, Bethesda, ML, USA) was used to determine the UCL thickness, UCL length, and humeroulnar joint gap width in mm. This software enables the researchers to calibrate each image to set a pixel/mm ratio (16.2 pixels/mm). After analysis, the key for randomization of the images was shared between the two researchers and applied to the dataset. From the 36 ultrasound images, each of the conditions had three measurements from which the mean was calculated. This resulted in 12 data points. The intraclass correlation coefficient for absolute agreement using a random effects model was determined for the three outcome variables to determine the inter-rater reliability of the data analysis (Table 1). The results can be considered acceptable [18].

Table 1. Intraclass Correlation Coefficients (ICC) between the two researchers for the three outcome variables. CI= confidence interval at 95%

	ICC	CI
Humeroulnar joint gap	0.75	0.68-0.82
UCL Length	0.81	0.66-0.89
UCL Thickness	0.82	0.65-0.89

Statistical analysis

The dataset of the investigator JvG was used for the statistical analysis, considering the sufficient level of reliability for the data analysis. To analyze the effect of handgrip force on the humeroulnar joint gap for the different levels of elbow valgus stress before pitching, a two-way (handgrip force [without, with] x elbow valgus stress [0N, 50N, 100N]) repeated measures analysis of variance (ANOVA) was used. To study the effect of repetitive pitching on UCL morphology and the humeroulnar joint gap for different levels of elbow valgus stress, a two-way (time [before pitching, after pitching] x elbow valgus stress [0N, 50N, 100N]) repeated measures ANOVA was used. To examine whether the effect of exerted handgrip force on the humeroulnar joint gap for the different levels of elbow valgus was different after compared to before repetitive pitching, a three-way (handgrip force [without, with] x elbow valgus stress [0N, 50N, 100N] x time [before pitching, after pitching]) repeated measures ANOVA was applied. Bonferroni post hoc pairwise comparisons were conducted to examine the significant interaction. The sphericity assumptions were valid and the data were normally distributed according to the Shapiro-Wilks tests and visual inspections of the histograms, q-q plots, and box plots. Significant differences were set at a level of $p<0.05$. Data were statistically analyzed using Jamovi (Jamovi project 2022, version 2.3) and visualized with Rstudio (Boston, MA,USA, version 2022.2.0.443).

RESULTS

Data regarding the humeroulnar joint gap from a total of thirteen of the fifteen participants were included in the statistical analysis (n=13). The researchers reached a consensus that the data of two participants were not sufficient in terms of the quality of the images to accurately measure the humeroulnar joint gap. The data regarding UCL thickness and UCL length was obtained and included in the statistical analysis for all participants (n=15). A total of 1260 fastballs were pitched, ranging from 60 to 110 fastballs per participant.

Effect of handgrip force on the humeroulnar joint gap

Figure 3A shows the mean humeroulnar joint gap in mm of 13 participants, for 0N, 50N, and 100N of imposed elbow valgus stress using the TELOS device, with and without exerted handgrip force. The mean humeroulnar joint gap varies from 3.01 (SD .77) mm to 4.24 (SD 1.11) mm. There was a significant main effect of elbow valgus stress, showing that the humeroulnar joint gap increases with increasing levels of elbow valgus stress (Table 2). Although the mean humeroulnar joint gap decreased with handgrip force at all levels of elbow valgus stress, the main effect of handgrip force and the interaction between handgrip force and elbow valgus stress were not significant for the humeroulnar joint gap (Table 2).

Table 2. Main and interaction effects for the repeated measures ANOVA concerning the effects of elbow valgus stress and handgrip force on the humeroulnar joint gap ***before*** *repetitive pitching.*

	F-value (df)	p-value	effect size (ηp^2)	Bonferroni		
				0N–50 N	0N–100N	50–100N
Elbow valgus stress	21.14 (2,24)	$p < 0.001$	0.638	$p = 0.001$*	$p < 0.001$*	$p = 0.123$
Handgrip force	0.45 (1,12)	$p = 0.515$	0.036			
Elbow valgus stress* Handgrip force	0.31 (2,24)	$p = 0.738$	0.025			

UCL morphology and humeroulnar joint gap after repetitive pitching

Figure 2A and 2B show the mean UCL length and thickness, respectively, before and after repetitive pitching, for the different levels of elbow valgus stress. The mean UCL length varies from 22.85 (SD 2.84) mm before to 23.63 (SD 3.29) mm after repetitive pitching. The mean UCL thickness varies from 5.67 (SD .95) mm before to 5.93 (SD .86) mm after repetitive pitching. There was no significant main effect of repetitive pitching on UCL length or UCL thickness (Table 3). There was also no significant main effect of elbow valgus stress on UCL length and UCL thickness, as well as no significant interaction with repetitive pitching.

Figure 2C shows the results of the humeroulnar joint gap of 13 participants, before and after repetitive pitching, without the handgrip force. There was no significant main effect of repetitive pitching on the humeroulnar joint gap (Table 3).

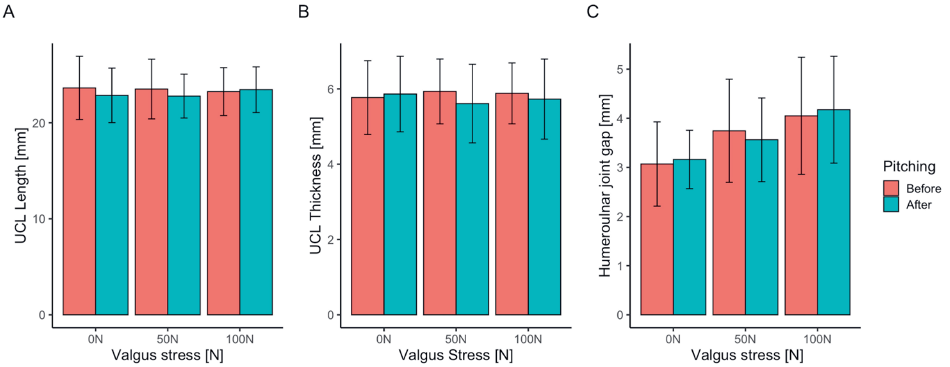

Figure 2. Panels A and B show the UCL length and UCL thickness, respectively, for the different levels of applied static elbow valgus stress (0, 50, 100) before and after repetitive pitching. Panel C shows the humeroulnar joint gap before and after repetitive pitching. Error bars represent the standard deviations.

Effect of handgrip force before and after pitching on the humeroulnar joint gap

Data before and after repetitive pitching were analyzed to determine the effect of handgrip force on the humeroulnar joint gap at different levels of elbow valgus stress (Figure 3). There was no significant three-way interaction between repetitive pitching (before vs after repetitive pitching), handgrip force and elbow valgus stress with respect to the humeroulnar joint gap ($F(2,24)=2.30$, $p=0.122$, $hp^2=0.161$).

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Table 3. Main and interaction effects of the two-way repeated measures ANOVA for repetitive pitching (before vs after repetitive pitching) and elbow valgus stress for UCL length, UCL thickness, and the humeroulnar joint gap ***without handgrip force****.*

	F-value (df)	p-value	effect size (ηp^2)	Bonferroni		
				0N–50N	0N–100N	50N–100N
Repetitive pitching						
UCL length	2.06 (1, 14)	*p* = 0.17	.129			
UCL thickness	1.67 (1, 14)	*p* = 0.22	.107			
Humeroulnar joint gap	0.11 (1, 12)	*p* = 0.75	.009			
Valgus stress						
UCL length	0.12 (2, 28)	*p* = 0.89	.008			
UCL thickness	0.09 (2, 28)	*p* = 0.91	.007			
Humeroulnar joint gap	16.81 (2,24)	*p* < 0.001 *	.584	*p*=0.011*	*p*=0.003*	*p*=0.008*
Repetitive pitching *						
valgus stress	1.22 (2, 28)	*p* = 0.31	.080			
UCL length	1.77 (2, 28)	*p* = 0.19	.112			
UCL thickness	3.30 (2, 24)	*p* = 0.06	.216			
Humeroulnar joint gap						

DISCUSSION

The aims of the study were to investigate the effect of handgrip force and repetitive pitching on the humeroulnar joint gap size and UCL morphology and to investigate whether handgrip force differently affects the humeroulnar joint gap for different levels of elbow valgus stress after, and also compared to before, repetitive pitching in asymptomatic baseball pitchers. No significant effect of the exertion of handgrip force on the humeroulnar joint gap for different levels of elbow stress was observed. In addition, the UCL morphology and humeroulnar joint gap were also not significantly affected by repetitive pitching for the different levels of elbow stress. Finally, the non-significant three-way interaction indicated that the change in humeroulnar joint gap for the combinations of handgrip force and elbow valgus torque was not different after repetitive pitching compared to before the pitching session.

As expected, and in concordance with the literature [19] the humeroulnar joint gap increased significantly with an increase in elbow valgus stress imposed by the TELOS device. This proves that the medial side of the elbow joint is loaded as a consequence of applied

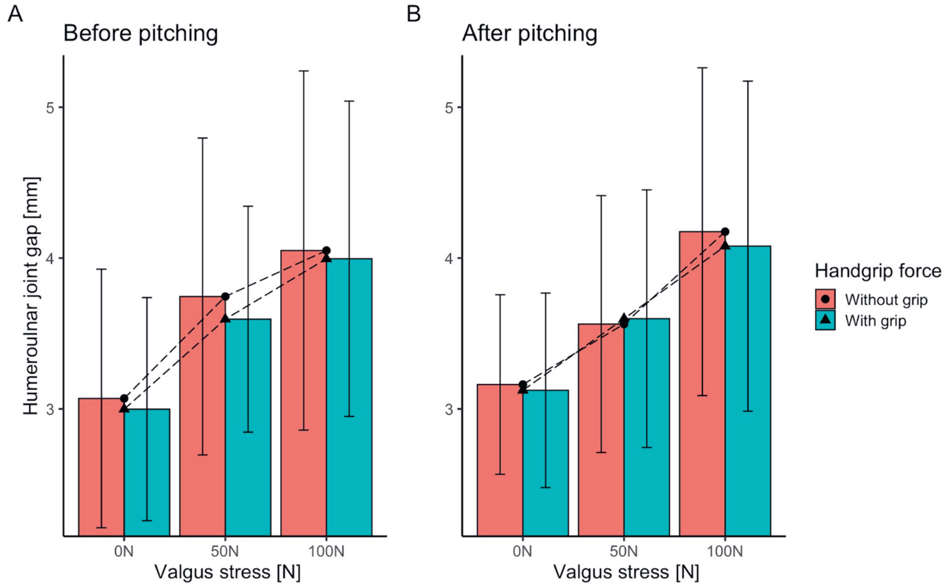

Figure 3. Panel A shows the mean humeroulnar joint gap (in mm) for the different levels of elbow valgus stress (0, 50, 100 N) without and with handgrip force ***before*** *repetitive pitching. Panel B shows the humeral ulnar joint gap* ***after*** *pitching. To visualize interaction effects, the dashed line with the dots shows the condition* ***without*** *handgrip force and the dashed lines with the triangles show the condition* ***with*** *handgrip force. Be aware, because of visualizing the three-way repeated measures ANOVA, the y-axis does not start at zero.*

valgus stress. Valgus stress is resisted by the UCL and counteracted by elbow muscles. Thus, an increase in valgus stress results in an increase in UCL load and elbow muscle load. A static mechanical calculation shows that the valgus stress of 50N and 100N is comparable with 12.5Nm and 25 Nm respectively. Assuming a distance of 25 cm from the handle on the forearm to the applied valgus stress (Figure 1). This is lower compared to the 50Nm peak external valgus torque under dynamic circumstances while pitching [7,8]. Thus, the humeroulnar joint gap might be even larger during pitching.

The elbow muscles have the potential to shield the UCL from high valgus torques while pitching [20]. We expected to find a decrease in the humeroulnar joint gap in pitchers in relation to handgrip force as other studies showed a decrease in the humeroulnar joint while maximal gripping in a general population of healthy males [21,22]. In contrast, the present results showed that the humeroulnar joint gap was not significantly reduced with handgrip force, independent of the levels of valgus stress imposed on the elbows of the participants in this study. The participants in our study, however, did not perform maximal handgrip force but applied a handgrip force of 20% of the maximum. Tsubono et al. (2022), published after our measurements, defined 50% maximal handgrip force as a cut-off point at which changes in the humeroulnar joint gap can be measured in a general male population [23]. Lower values of handgrip force could explain why we did not find a significant effect on the size of the humeroulnar joint gap. Elbow muscles are active during pitching and have the potential to stress shield the UCL [20]. However, the magnitude of the force exerted by the elbow muscles seems related to the humeroulnar joint gap and thus may affect the extent of stress shielding during pitching. Therefore, future studies should investigate how elbow muscle force is related to the humeroulnar joint gap and thus with the UCL loading during pitching.

In a single session, the results did not reveal a significant effect of repetitive pitching for the different levels of valgus stress on the humeroulnar joint gap and UCL thickness and length. We expected, based on the results of Hattori et al. (2018), that the humeroulnar joint gap would increase after a session of repetitive pitching without considering the effect of handgrip force. Despite a comparable ball speed, the pitchers in our study were eight years older compared to the high school pitchers in the study of Hattori et al. Younger and less experienced pitchers, who have therefore been less exposed to mechanical load at their elbows in the past, have a thinner UCL and a more lax humeroulnar joint gap compared to older and more experienced pitchers [24]. Older pitchers are exposed more frequently to higher magnitudes of valgus torques while pitching during their lifetime. Adaptations increase the strength of the UCL and possibly the elbow muscles and thus elbow the shielding effect of elbow muscles during pitching. This might explain why the frequency of pitch number might have more impact on the humeroulnar joint gap in younger pitchers compared to older pitchers. Another explanation for not finding an effect on elbow response might be that the exposure was too low. The participants were instructed not to throw at least two days before the measurements. Pitching 100 balls during training or a game is within the general exposure of a non-fatigued pitcher. An increase in exposure, by pitching more balls might have shown an effect on elbow response in adult pitchers.

After repetitive pitching, the shielding effect of the elbow muscles might be reduced as a result of muscle fatigue. The results of the present study did not show that for the humeroulnar joint gap the interaction between handgrip force and valgus stress was different after repetitive pitching compared to before the pitching session. On the one hand, this could mean that the forearm muscles are able to help stabilize the elbow joint after a single session of repetitive pitching in the same way as before. High school pitchers have shown a decrease in maximal handgrip strength after repetitive pitching, but this reduction was not correlated with the humeroulnar joint gap quantified under gravity stress and without handgrip force [25]. Indicating that repetitive pitching does not influence muscle force in relation to the humeroulnar joint gap, and thus influences the stress shielding of the UCL. On the other hand, as explained above, we did not find a decrease in the humeroulnar joint gap with the applied 20% of the maximal handgrip force, whereas higher percentages of handgrip force decreased the humeroulnar joint gap [23]. The effect of fatigued muscles might become detectable at a higher magnitude of handgrip force. Therefore, it should be investigated if elbow muscles after repetitive pitching are less capable of counteracting valgus stress at higher percentages of handgrip force.

That the results did not show a decrease or increase in the humeroulnar joint gap, respectively, while gripping or after repetitive pitching, does not necessarily mean that the forearm muscles are not counteracting the external valgus torque during pitching. Because, if the muscles are not counteracting the valgus torque during pitching, we might have seen an increased humeroulnar joint gap as a response to repetitive pitching. Observed differences in forearm muscle activation between baseball pitchers with and without elbow symptoms may support this explanation. Glousman et al. (1992) found a decrease in activation in the forearm muscles (flexor carpi radialis and pronator teres) in symptomatic pitchers compared to asymptomatic pitchers during pitching, which could be associated with a higher UCL load in the symptomatic pitchers during pitching. However, within a single pitching session, we are not able to detect changes in the elbow responses in asymptomatic baseball pitchers.

It is clinically relevant to understand the elbow muscle stress shielding effect and how alterations in the humeroulnar joint gap and maladapting in UCL morphology are related to UCL injuries. Static ultrasound of the UCL morphology and humeroulnar joint gap showed changes in the response to elbow stress between in- and off-season [15]. Therefore, changes in thickness and humeroulnar joint gap seem valuable while measuring over a longer period to quantify the response to elbow stress, instead of a single session. In addition, changes in the humeroulnar joint gap with handgrip force with an elbow exposed to valgus stress might become detectable as a reduction of elbow muscle force, due to fatigue over a longer period instead of a single session.

The humeroulnar joint gap, the UCL thickness and length are not showing an abnormal response after repetitive pitching. This does not mean that the UCL does not respond to pitching. In situ studies showed microdamage in ligaments under submaximal loading. Comparable microdamage in the UCL morphology cannot be detected with the measurement setup in this study. However, changes in the ligament morphology might become visible after a few hours or a few days as an inflammatory reaction might thicken the ligament [26]. Only the elbow response was measured directly after pitching which is a limitation of this study. Another limitation of this study is that ultrasound imaging may seem an objective method to assess properties of anatomical structures, but it is associated with rater-dependent measurement error when taking the actual images and when analyzing the images for distances. Therefore, investigating differences within an individual becomes difficult because measurement errors might be larger than differences or changes that are clinically relevant. To limit the measurement error, the same static valgus stresses with the use of a TELOS device were applied, and bony landmarks were marked to locate the arm in the same position before and after pitching. While analyzing the data, our results showed moderate to good intra-rater reliability for all three outcome variables, comparable with other studies [15].

CONCLUSION

The humeroulnar joint gap increases with increasing levels of static elbow valgus stress. Handgrip force, used as a proxy for the stabilizing effect of the flexor pronator mass muscle, did not affect these changes in the humeroulnar joint gap, and higher levels than 20% of the maximal handgrip force are likely needed to decrease the joint gap. In asymptomatic pitchers, repetitive pitching did not influence the humeroulnar joint gap, nor the UCL morphology, nor the interaction between handgrip force and elbow valgus stress. To conclude, adult baseball pitchers do not respond to elbow stress after a single pitching session in the humeroulnar joint gap and UCL length and thickness. Clinically it seems more relevant to quantify the elbow response over sessions and seasons while considering the elbow muscle forces.

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Ik vertel hier over de toepassing
en het gebruik van draagbare sensoren.

PART III

Preventing injuries with data-driven wearable sensors and real-time feedback

CHAPTER 8

Predicting elbow load based on individual pelvis and trunk (inter)segmental rotation in fastball pitching

Submitted in: Sports Biomechanics

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ABSTRACT

The baseball pitch is a full-body throwing motion that through its repetitive nature exposes the elbow to significant loads, leading to a high incidence of elbow injuries. Elbow injuries in pitching are often attributed to high external valgus torques as these are generally considered to be a good proxy for the load on the elbow structures such as the Ulnar Collateral Ligament. Monitoring elbow load for an individual pitcher during the game or training can provide actionable insight for the prevention of overuse injuries. Eleven male youth elite baseball pitchers (age 17 ± 2.2 years) threw 25 fastballs at full effort off a mound. Two-level varying-intercept, varying-slope Bayesian models were used to predict external valgus torque based on (inter)segmental rotation in fastball pitching with pitcher's weight and height added to strengthen the individualization of the prediction. The results revealed the high predictive performance of the models including a set of kinematic parameters trunk peak angular velocity and the intersegmental timing between the pelvis and trunk peak angular velocities. Such an approach allows individualized prediction of the external valgus torque for each pitcher, which has a great practical advantage compared to group-based predictions in terms of injury assessment and injury prevention. Trunk peak angular velocity and the separation time can be recorded with wearable sensors in the future. Such data recorded with sensors may be used as input for the proposed model and provide actionable insight for injury prevention in baseball pitching.

INTRODUCTION

The baseball pitch is a full-body throwing motion that, due to its repetitive nature, exposes the elbow to significant loads [1,2]. This leads to a high incidence of overuse elbow injuries among baseball pitchers at all levels of play [3-5]. The injury aetiology seen in youth and adult pitchers has been linked to high elbow external valgus torques [5,6]. The external valgus torque imparts a tensile force to the medial elbow structures [8,9], which in combination with repetitive loading results in injuries to the medially located ulnar collateral ligament (UCL). This indicates that external valgus torque can be used as a proxy of the elbow load [10,11]. Thus, continuous and prospective elbow load monitoring, both in training and in game, plays an essential role in pitchers' performance enhancement whilst minimizing the risk of elbow injuries [12].

To assess the external valgus torque, it is important to understand pitching mechanics. Pitching mechanics can be described by the two well-known biomechanical principles; the summation of speed principle, also known as the kinetic chain, and the principle of optimal coordination of partial momenta [13]. Both principles consider the human body as a linked segment model and explain the biomechanics of pitching in terms of peak angular velocities of body segments and their intersegmental timing. Overhead throwing motion, such as baseball pitching, is more likely to follow the kinetic chain [13]. Regardless of the principle, the high end-point velocities imparted to the ball depend on the contribution of all segments [14].

In the pitching motion, energy from the legs is transferred to the pelvis [15] and subsequently transferred via the trunk up to the throwing arm [16]. In such complex sequential movement, pelvic and trunk kinematics play an essential role in transferring the momentum generated by the lower extremities to the upper extremity. Optimal proximal-to-distal timing between the pelvis and trunk results in the maximized ball velocity at the most distal end [2,13]. The timing between the pelvis and trunk peak angular velocities is also referred to as separation time. If this kinematic sequencing or timing is not optimal, energy is dissipated into the upper extremity which results not only in decreased ball velocity [13,17], but also the potentially increased risk of injuries [18].

Manipulation of biomechanical parameters within the kinetic chain may affect the external valgus torque and help in managing the risk of excessive UCL loading. By increasing trunk peak angular velocity, pitchers may throw faster, but with an increased external valgus torque [19]. There is likely a threshold above which the exceeded external valgus torque represents a significant injury risk. The efficiency of the kinetic chain may contribute to the reduction of external valgus torque levels at this critical point while still maintaining high levels of ball speed and overall pitching performance [20].

We expect that the levels of external valgus torque will differ between pitchers due to variations in anthropometric measures, pitching technique, level of play, and within-individual load variability [21,22]. Multilevel modelling is well-suited for the analysis of repeated measurements that are considered to be “clustered” within individual pitchers [23]. Such measurements are assumed to be independent as the observations within a cluster are more likely to be similar than observations from different clusters. Since regression- and ANOVA-based techniques do not meet this assumption, they are not fully appropriate for dealing with this type of data structure. Multilevel modelling techniques for repeated measurements allow us to analyse the relationships between data collected at the pitcher- or group-level, and data collected on variables that change with trials at the unit- or individual-level [24].

The aim of the study is to contribute to monitoring the external valgus torque in baseball pitching by developing a prediction model based on the pelvis and trunk peak angular velocities and their separation time. It is hypothesized that external valgus torque for an individual pitcher can be predicted based on the pelvis and trunk peak angular velocity and separation time between them. In addition, we expect that the model including both pelvis and trunk peak angular velocity and their separation time will have the best predictive performance.

METHODS

Participants

Eleven male Dutch national (AAA) youth elite baseball pitchers participated in the study, with a mean age of 17.4 (± 2.2) years, mean body mass of 80.6 (± 11.7) kg, mean body height of 1.86 (± 6.3) m and mean ball speed was 34.0 ± 1.4 m/s (76.6 ± 3.2 mph). Only participants without present musculoskeletal injuries and who did not have musculoskeletal injuries in the last six months were included in this study. Participants gave written consent to use the data information for analysis and publication after being fully informed. If participants were under 16 years, their parents or guardians were informed about the study and required to sign an informed consent form. This research was conducted as part of a larger study [22] and was performed in accordance with the Declaration of Helsinki and the local ethics committee. The local ethics committee of the Faculty of Behavioral and Movement Sciences (VCWE) approved the study protocol (reference number: VCWE2019-033).

Procedure

Data collection was performed in an indoor movement laboratory at the Royal Netherlands Football Association. The participants wore sneakers, athletic stretch shorts, catching gloves, and no shirts. Forty-three reflective markers were attached with double-sided tape on the bony landmarks. Participants performed their regular warming-up, which contained stretching, drills, and several warming-up pitches. Subsequently, they threw several pitches from the mound to become familiar with the research setup. The participants were instructed to throw 25 fastball pitches at full effort toward a squared strike zone (height 0.64m; width 0.38m). The pitching rubber was attached to the top of the mound at 0.55m above the ground and had a distance of 18.44 m to the home plate. The time between each pitch was not controlled but regulated by the pitcher himself, like in a normal game.

Data acquisition

Full body position data of the pitchers were collected with a VICON eight-camera motion capture system. Data were sampled at 400Hz (model V5; Vicon Motion Systems Ltd., Yarnton, UK). The ball speed was measured with a radar gun positioned next to the strike zone (Stalker Radar, Plano, TX, USA).

Data processing

Three-dimensional position data of the fourteen bony landmarks were used in this study (Table 1). The position data were interpolated with a third-order cubic spline polynomial and filtered with a fourth-order Butterworth filter with a cut-off frequency of 12.5 Hz. To calculate the segment angular velocities and the elbow valgus torque an anatomical coordinate system was constructed for the pelvis, trunk, upper arm, forearm, and hand according to the ISB recommendations [25].

The segment angular velocities were computed directly from the rotation matrices following the method described in the study of Zatsiorsky [26]. Subsequently, the Euclidean norm was calculated over all three different axes. The exact moments of peak angular velocities were found analytically by fitting a second-order polynomial function to eleven measured data points. These data points included five samples before and after the samples closest to the maximum angular velocity. The separation time was calculated as the time interval between the pelvis and trunk peak angular velocities [17].

Elbow joint torques were calculated based on the top-down method based on the Newton-Euler equation of motion, starting in the hand of the throwing arm. The segment center of mass position and the moments of inertia were estimated according to Zatsiorsky [26] and De Leva et al. [27]. The baseball was modeled with a mass of 0.145kg attached to the hand. The mass linearly reduced by 10% over the last ten samples (0.025s) before ball release. Ball release was defined as the moment the wrist exceeded the position of the elbow in the forward direction. The elbow joint coordinate system was expressed in the anatomical coordinate system of the forearm, located in the middle between the medial and lateral humeral epicondyle. The time series of external elbow valgus torque was determined for each individual pitch, covering the duration from foot contact to ball release. Subsequently, the peak external valgus torque was derived from this time series data. The time series of the segment angular velocities and external valgus torque were visually checked for errors and mistakes.

Table 1. Bony landmarks used in the study.

Marker number	Bony landmarks
1	Third proximal interphalangeal
2	Ulnar process styloid
3	Radial process styloid
4	Lateral humeral epicondyle
5	Medial humeral epicondyle
6	Acromion
7	Xiphoid process
8	Incisura jugularis
9	7th cervical vertebrae
10	8th thoracal vertebrae
11& 12	Left and right anterior superior iliac spine
13 &14	Left and right posterior superior iliac spine

Statistical methods and modelling

For the *i*-th throw, let y_i, x_{i1}, x_{i2}, x_{i3}, x_{i4} and denote the external valgus torque, pelvis peak angular velocity, trunk peak angular velocity, separation time, weight and height respectively. Set x_1= (x_{i1},x_{i2},x_{i3}) and u_i = (x_{i4},x_{i5}). We aim to model the relationship between y_i and (x_i,u_i). The simplest type of model for this is the linear model given by

$$y_i \mid \beta_0, \beta, \sigma^2 \overset{\text{ind}}{\sim} \mathcal{N}(\beta_0 + \beta' x_i + \gamma' u_i, \sigma^2) \quad \text{(Equation 1)}$$

However, note that the data from repeated measurements such as in this study have the structure in which observations on an individual level (pelvis and trunk peak angular velocities, separation time, external valgus torque) are nested within baseball pitchers on a group level. As such, a simple linear model like equation (1) will not be able to take into account that throws by the same pitcher tend to be more similar than throws by different pitchers. This phenomenon is illustrated in Figure 1, where we have also included weight and height to see how external valgus torque is affected by these characteristics.

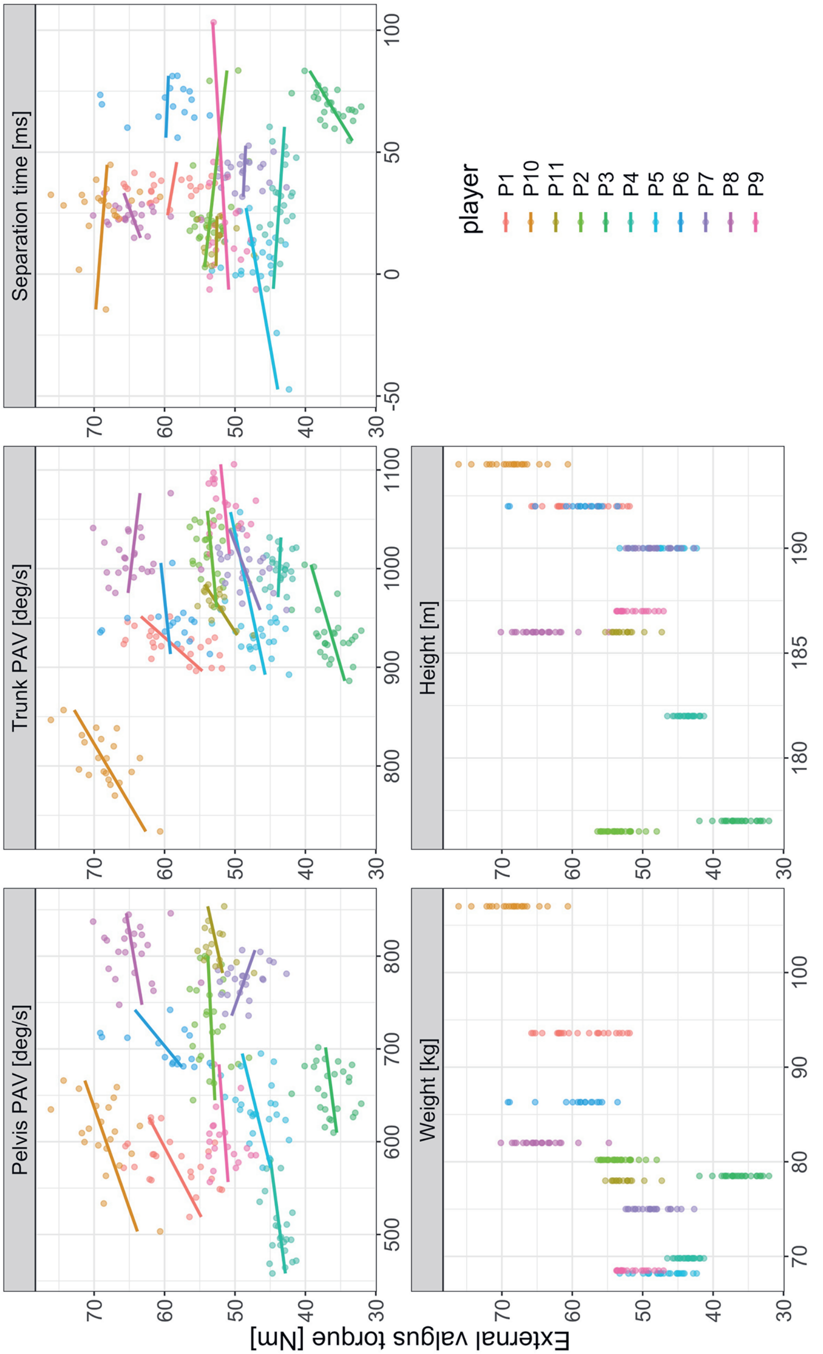

Figure 1. Exploratory data analysis for the relation between external valgus torque and pelvis peak angular velocity (pelvis PAV), trunk peak angular velocity (trunk PAV) and separation time. In each subpanel, the influence of one predictor on external valgus torque is displayed. In the upper three panels, least-squares fits have been superimposed (separately, for each player).

This figure strongly suggests a *two-level linear model, with both varying intercepts and varying slopes*. The need for such a model is most easily seen from the panel with “trunk PAV”. If we would fit a single line through the data, this would imply a negative relationship between external valgus torque and trunk peak angular velocity (trunk PAV), whereas for each individual player, this relationship is positive. This can be seen as an instance of Simpson’s paradox, well known in statistics. Specifically, we propose the following model:

$$y_{\mathrm{i}} \mid \alpha_1, \ldots, \alpha_J, \beta_1, \ldots, \beta_J, \sigma^2 \overset{\mathrm{ind}}{\sim} \mathcal{N}(\mu_{\mathrm{i}} + \gamma' u_{\mathrm{i}}, \sigma^2)$$
$$\mu_{\mathrm{i}} = \alpha_{\mathrm{j[i]}} + \beta'_{\mathrm{j[i]}} x_{\mathrm{i}} \qquad \text{(Equation 2)}$$

The symbols $\overset{\mathrm{ind}}{\sim}$ and $\overset{\mathrm{iid}}{\sim}$ denote “independently distributed as” and “independent and identically distributed as”. We have *J*=11 – the total number of pitchers in the study – and *j*[*i*] = *k* if the *i*-th throw corresponds to *k*-th pitcher in the dataset. We follow the Bayesian approach to statistics, where unobserved quantities get assigned a prior distribution, reflecting the (lack of) information we have about their values before collecting the data. We impose $\alpha_1, \ldots, \alpha_{\mathrm{J}} \overset{\mathrm{iid}}{\sim} \mathcal{N}(0, \sigma_\alpha^2)$, $\beta_1, \ldots, \beta_{\mathrm{J}} \overset{\mathrm{iid}}{\sim} \mathcal{N}_3(0, \sigma_\beta^2 I_{3\times 3})$ and $\gamma \sim \mathcal{N}(0, \sigma_\gamma I_2)$. We took default values from rstanarm (version 2.21.1) [28], which means $\sigma_\alpha = \sigma_\beta = \sigma_\gamma = 2.5$. Taking mean-zero priors is justified as we standardized (i.e. transformed to zero-mean and unit standard deviation) each of the predictors before fitting the model. Also for σ, σ_α and σ_β we took the default prior mean-one Exponential distribution from rstanarm [28].

We used leave-one-group-out cross-validation (LOGO-CV) to select the model with the best predictive performance. LOGO-CV is a specific type of *k*-fold cross-validation that utilizes data from each individual pitcher as a test set. The number of folds, therefore, equals the number of pitchers. For every fold, the model is trained on data from *J*-1 pitchers and tested on the data from the one left-out pitcher. Models were compared according to their expected log-predictive density (*elpd*) as described in the work of Vehtari [29,30].

We used posterior predictive distributions to generate data samples whose average is then compared to the real data. We interpret the generated data as the data sample that we might collect tomorrow if the data collection process remains the same as it initially was. Posterior predictive checks were used to test the performance of the model and visually inspect how much generated data samples match the observed ones.

RESULTS

A total of 240 throws by 11 pitchers were included in the analysis. Descriptive statistics of included variables are shown in Table 2.

Table 2. Descriptive statistics for the variables included in the analysis.

Variables	Mean ± Standard Deviation
Pelvis peak angular velocity [deg/s]	669.87 ± 99.06
Trunk peak angular velocity [deg/s]	964.85 ± 68.61
Separation time [ms]	32.70 ± 22.98
Weight [kg]	80.47 ± 11.11
Height [m]	186.26 ± 5.85
External valgus torque [Nm]	52.76 ± 9.59

Expected log-predictive density *(elpd)* was a chosen measure of model fit and it was subsequently used to compare models for model selection. The difference in *elpd* of the fitted two-level varying-intercept, varying-slope Bayesian models is shown in Figure 2. Models include various combinations of observed kinematic predictors (P – pelvis peak angular velocity, T – trunk peak angular velocity, S – separation time) with the addition of pitcher's weight (W) and height (H) to all the models. The ordering of the models in Figure 2 reveals that the model including a set of predictors TSWH showed the best predictive performance, and it is therefore the selected model. Table 3 shows parameter estimates from the selected model TSWH, based on a table generated by shinystan [31]. The small *elpd* differences between the selected model TSWH and the second ranked model TWH indicate almost similar performance in predicting external valgus torque.

The performance of the final model TSWH was tested through a posterior predictive check. In Figure 3 the average of the data samples generated from the posterior predictive distributions is compared to the observed data. If the model is a good fit for the data, then observed and simulated data should be aligned. The posterior predictive check shows that the observed data are more dispersed compared to the average of the generated data samples from the posterior predictive distributions. Bayesian conditional R^2 value is 0.916 (95% CI [0.899, 0.931]), and marginal R^2 value 0.927 (95% CI [0.847, 0.969]), where CI is a confidence interval. The marginal R^2 considers only the variance of the fixed effects, while the conditional R^2 takes both the fixed and random effects into account [32].

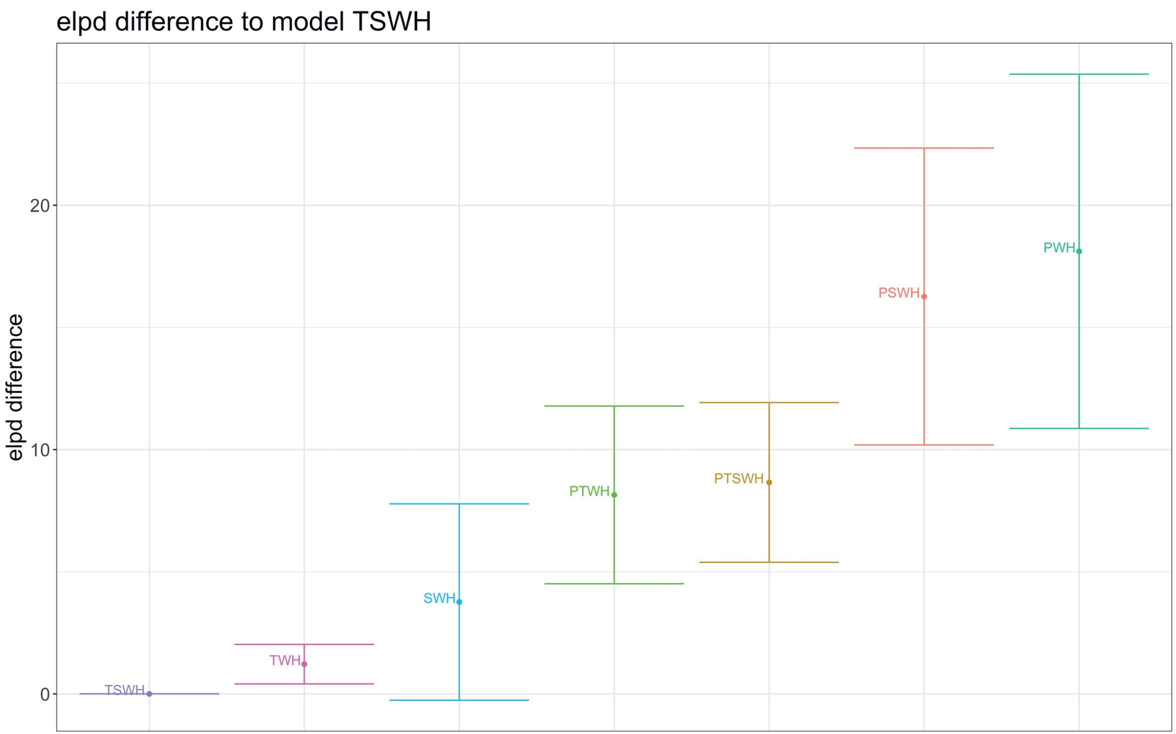

Figure 2. Estimates of absolute elpd difference (dot) using leave-one-group-out cross-validation. Vertical error bar for each model indicates the standard error of the elpd difference estimates. The order on the x-axis follows the ranking starting with the model with best predictive performance on the left. Predictors included in the analysis are pelvis peak angular velocity (P), trunk peak angular velocity (T), separation time (S), pitcher's weight (W) and height (H).

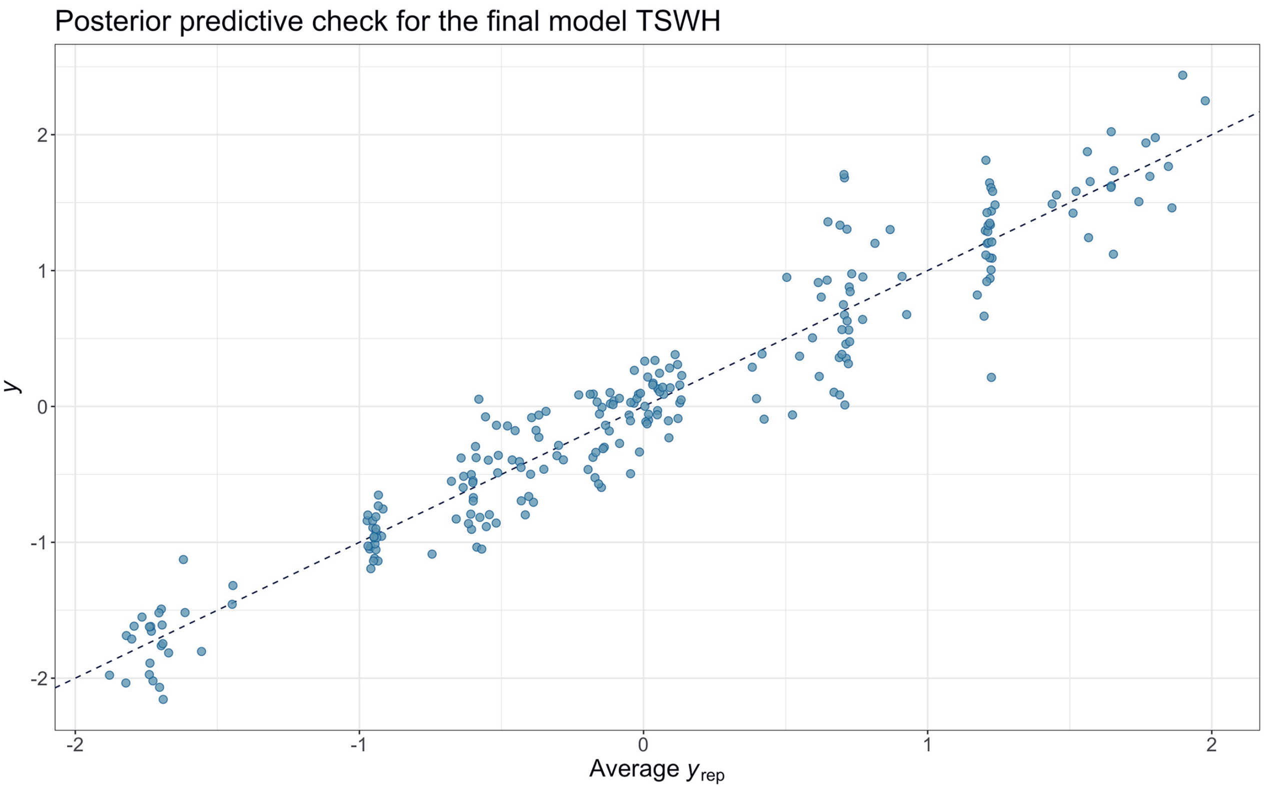

Figure 3. Posterior predictive checks compare the observed outcome variable y to the average of simulated datasets y_rep from the posterior predictive distribution for the selected model TSWH. The model includes a set of predictors of trunk peak angular velocity (T), separation time (S), pitcher's weight (W), and height (H). Bayesian conditional R2 value is 0.916 (95% CI [0.899, 0.931]), and the marginal R2 value 0.927 (95% CI [0.847, 0.969]), where CI is a confidence interval. The marginal R2 considers only the variance of the fixed effects, while the conditional R2 takes both the fixed and random effects into account [32].

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Table 3. Parameter estimates for the final model TSWH. Predictors are trunk peak angular velocity (Trunk_PAV), separation time (Separation), pitcher's weight (Weight), and height (Height). The standard deviation of the errors is called sigma and the variance-covariance matrix of the pitcher-specific deviations from the common parameters is called Sigma.

	mean	**SD**	**2.5%**	**25%**	**50%**	**75%**	**97.5%**
Weight	0.8	0.2	0.3	0.6	0.8	0.9	1.2
Height	0.4	0.2	0	0.3	0.4	0.5	0.8
b[(Intercept) Participant 1]	-0.3	0.3	-0.8	-0.4	-0.3	-0.1	0.3
b[(Intercept) Participant 10]	0.3	0.5	-0.6	0	0.3	0.6	1.2
b[(Intercept) Participant 11]	0.2	0.1	-0.1	0.1	0.2	0.2	0.4
b[(Intercept) Participant 2]	0.6	0.4	-0.1	0.4	0.6	0.9	1.4
b[(Intercept) Participant 3]	-0.8	0.4	-1.5	-1	-0.8	-0.6	-0.1
b[(Intercept) Participant 4]	0.1	0.2	-0.4	-0.1	0.1	0.2	0.5
b[(Intercept) Participant 5]	0.1	0.3	-0.5	-0.1	0.1	0.3	0.8
b[(Intercept) Participant 6]	0	0.2	-0.5	-0.2	-0.1	0.1	0.4
b[(Intercept) Participant 7]	-0.4	0.2	-0.9	-0.6	-0.4	-0.3	0
b[(Intercept) Participant 8]	1.1	0.1	0.9	1.1	1.1	1.2	1.4
b[(Intercept) Participant 9]	0.5	0.3	-0.1	0.3	0.5	0.7	1.1
b[Trunk_PAV Participant 1]	0.7	0.3	0.2	0.5	0.7	0.8	1.2
b[Separation Participant 1]	0	0.1	-0.3	-0.1	0	0	0.2
b[Trunk_PAV Participant 10]	0.4	0.1	0.1	0.3	0.4	0.5	0.7
b[Separation Participant 10]	0	0.1	-0.2	-0.1	0	0	0.1
b[Trunk_PAV Participant 11]	0.3	0.2	-0.1	0.1	0.3	0.5	0.8
b[Separation Participant 11]	0	0.1	-0.2	-0.1	0	0	0.2
b[Trunk_PAV Participant 2]	0.1	0.1	-0.2	0	0.1	0.2	0.4
b[Separation Participant 2]	0	0.1	-0.2	-0.1	0	0	0
b[Trunk_PAV Participant 3]	0.3	0.1	0	0.2	0.2	0.3	0.5
b[Separation Participant 3]	0	0.1	-0.2	0	0	0	0.2
b[Trunk_PAV Participant 4]	0	0.2	-0.4	-0.1	0	0.1	0.4
b[Separation Participant 4]	0	0.1	-0.1	-0.1	0	0	0.1
b[Trunk_PAV Participant 5]	0.2	0.1	-0.1	0.1	0.2	0.2	0.4
b[Separation Participant 5]	0	0.1	-0.1	0	0	0.1	0.2
b[Trunk_PAV Participant 6]	0.1	0.2	-0.3	-0.1	0.1	0.2	0.5
b[Separation Participant 6]	0	0.1	-0.2	0	0	0	0.1
b[Trunk_PAV Participant 7]	0.2	0.2	-0.1	0.1	0.2	0.4	0.6
b[Separation Participant 7]	0	0.1	-0.2	-0.1	0	0	0.1
b[Trunk_PAV Participant 8]	0	0.2	-0.3	-0.1	0	0.1	0.3
b[Separation Participant 8]	0	0.1	-0.1	0	0	0	0.2
b[Trunk_PAV Participant 9]	0.1	0.1	-0.2	0	0.1	0.2	0.4
b[Separation Participant 9]	0	0	-0.1	0	0	0	0.1
sigma	0.3	0	0.3	0.3	0.3	0.3	0.3
Sigma[Participant:(Intercept),(Intercept)]	0.4	0.2	0.1	0.3	0.3	0.5	0.9
Sigma[Participant:Trunk_PAV,Trunk_PAV]	0.1	0.1	0	0.1	0.1	0.2	0.3
Sigma[Participant:Separation,Trunk_PAV]	0	0	-0.1	0	0	0	0

DISCUSSION

Poor pitching mechanics [33] and overloading of the pitching arm can negatively affect pitching performance and at the same time put the elbow joint at great risk of injuries [11,34]. Therefore, estimation of the elbow load based on pitching mechanics is an important step toward monitoring the elbow load in the field. This study shows promising results of Bayesian hierarchical models in the prediction of the external valgus torque, used as a proxy of elbow load, based on (inter)segmental rotation in fastball pitching.

The results show that it is possible to predict the elbow external valgus torque based on the pelvis and trunk kinematics and separation time. Although it was hypothesized that the model including all three parameters would have the best performance, according to LOGO-CV the best predictive model is TSWH which includes peak trunk angular velocity, separation time, weight, and height (TSWH) (Bayesian conditional R^2 value is 0.916, marginal R^2 value is 0.927). The reason why the pelvis angular velocity was not included in the final model might be explained by the fact that the trunk angular velocity contains information from the proximal pelvis segment according to the proximal-to-distal sequence. The contribution of the separation time to the prediction of the external valgus torque indicates the importance of optimal timing between the pelvis and trunk segments in the kinetic chain for safe and efficient pitching. The trunk can produce a lot of power due to its segmental mass, although proper timing is needed for optimal contribution to the ball speed [35,36]. The increase in trunk rotation does not only increase the ball speed, but it increases the external valgus torque as well [19]. In line with our results, several studies showed a relationship between trunk kinematics and the external valgus torque [19,35]. In addition, we showed that it is possible to predict the external valgus torque for individual pitchers based on their peak trunk angular velocity and the separation time.

Predictions of the external valgus torque based on the trunk peak angular velocity and the separation time are important in relation to elbow injuries. Manipulation of these biomechanical parameters with training increases the ball speed [38] and may decrease the external valgus torque [19]. However, a pitcher throwing according to an optimal kinetic chain, with a reduced level of external valgus torque is still at risk of sustaining an injury due to repetitive pitching. Therefore, monitoring the external valgus torque is important for managing the risk of excessive elbow loading. Taking into account that the values of external valgus torque vary among pitchers of different ages, levels of play [21], and the variability within-individual pitchers [22], understanding the elbow loading for each pitcher based on his individual characteristics and pitching mechanics may be the base for the development of an "early warning system" for safe and efficient pitching.

This paper introduces the application of Bayesian hierarchical models to repeated measurements of pitching kinematics, kinetics, and temporal parameters. They account for the within-pitcher similarity and at the same time allow for the gradation of differences between the pitchers in the prediction of the external valgus torque. The small difference in *elpd* between the selected model TSWH and the model TWH ranked second in terms of LOGO-CV refers to similar predictive performance (Figure 2), in addition, a post hoc posterior predictive checks analysis reveals similar results for the TWH model compared to the TSWH model. Predicting the external valgus torque with the TWH model is practically relevant as only a single variable (trunk peak angular velocity) should be measured. Although the selected final model (TSWH), contains the separation time next to the trunk peak angular velocity. The separation time includes information about the timing between segments and is related to the efficiency of the kinetic chain. It is shown that fatigue influences the hip-to-shoulder separation time, resulting in a breakdown of the kinetic chain [39]. Therefore, in terms of monitoring over a longer period, we expect that it is important to measure both the trunk angular velocity and the separation time in order to predict the external valgus torque.

One of the limitations of this study is the inclusion of only fastball pitches. Studies have shown that the elbow load is lower in the change-up or breaking balls [40], however, the link between the torso kinematics and elbow load has not been investigated yet. Furthermore, the current study had a very low sample size (n = 11) and included repeated measurements from a single data collection event. The lack of longitudinal data collection limits the detection of patterns in elbow loading based on pitching mechanics. A larger data sample including a wider range of age groups and levels of play may improve the predictive performance and lower the uncertainty in predicted external valgus torque. Collecting longitudinal data, including reported injuries, would allow us to link the loading on the elbow joint to injury occurrence in individual pitchers. This information can be used as a base for setting a pitcher's injury threshold. If the elbow loading exceeds the estimated threshold, the pitcher will likely be injured. Such information may help coaches in training subscription and modification of the pitching technique that leads to reducing the external valgus torque and therefore the risk of elbow injury.

The final model proposed in this paper considered the practical relevance of trunk kinematics and separation time between the pelvis and trunk in managing injury risk and shows its potential utilization for elbow load monitoring on the field. Trunk peak angular velocity and the separation time can be recorded with wearable sensors, like inertial measurement units [23,41]. Such data recorded with sensors may be used as input for the proposed model and provide actionable insight for injury prevention in baseball pitching.

CONCLUSION

In this study, a model has been proposed to predict elbow load based on the pelvis and trunk peak angular velocities and separation time between them. Application of Bayesian hierarchical models on data including the trunk peak angular velocity and the separation time between the pelvis and trunk peak angular velocities show promising results for the prediction of the external valgus torque in fastball pitching. Such an approach allows individualized prediction of the external valgus torque for each pitcher, which has a great practical advantage compared to group-based predictions in terms of injury assessment and injury prevention.

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CHAPTER 9

General discussion

The general aim underlying the present dissertation was to establish biomechanical injury mechanisms related to the UCL in baseball pitchers. Knowledge of these mechanisms can eventually be used to develop an 'early warning system' to prevent baseball pitchers from UCL injuries. This dissertation is divided into three distinct parts to achieve the overarching aim.

The first part of this dissertation, "the single pitch", aimed to describe the relationship between the UCL properties and elbow stabilizers for UCL loading during pitching. The external valgus torque during pitching is approximately 5Nm to 85Nm higher than the ultimate in-vitro UCL torque. Other functional and structural elbow stabilizers explain that the UCL does not tear immediately in a single pitch (*Chapter 2)*. During a single baseball pitch, stress shielding of the elbow muscles (functional stabilizers) at the critical elbow load can function as a protection mechanism in relation to UCL injuries (*Chapter 3)*

In the second part of this dissertation, we investigated the effect of "repetitive pitching" in relation to elbow load. The central question was: Why does one pitcher sustain a UCL injury, and another does not? The simplified explanatory simulation model illustrates that all pitchers are at risk of sustaining an injury; higher load variability, higher magnitude, and longer exposure all increase this risk (*Chapter 4)*. The presence of, and differences in, within-individual external valgus torque variability among elite baseball pitchers seems, in addition to the load magnitude, an important variable in injury assessment and possibly in injury prevention (*Chapter 5)*. The elbow load magnitude and within-individual load variability differ significantly among pitchers with repetitive pitching. The significant variations in elbow muscle activation among pitchers in relation to repetitive pitching show that the stress shielding function of the elbow muscles cannot be considered a constant variable (*Chapter 6).* The elbow response was not affected by 20 % of the maximal handgrip force for different levels of static valgus stress after repetitive pitching compared to before (*Chapter 7).*

In the third part of this dissertation, "Preventing injuries with data-driven sensors and real-time feedback", we investigated if we could predict the external valgus torque in the field based on body kinematics *(Chapter 8)*. It is concluded that individual elbow load can be predicted based on pelvis and trunk peak angular velocities in the field. Excellent predictions are only possible with the condition that the prediction is a mix between group and individual levels.

INJURY MODEL

In parts I and II of this dissertation biomechanical variables are identified that play a role in UCL injury mechanisms in baseball pitching. These biomechanical variables, in combination with the knowledge of the stress-strain-dynamic capacity model (Figure 1) provide us with

Figure 1. The injury model application interface includes the implementation of the selected biomechanical variables. The various buttons are: pitch number, elbow load magnitude (Nm), elbow load variability (Nm), shielding effect (N) and time. The UCL injury threshold can be set manually.

the following key variables for an (UCL / elbow) injury model for an individual baseball pitcher: pitch number, elbow load magnitude, elbow load variability, shielding effect, injury threshold, and recovery/time. We developed an application of this injury model to experiment with the settings of the various variables, shown as buttons that can be adjusted (Figure 1).

The injury model shows that focusing on solely one factor cannot explain or prevent athletes from UCL injuries. Only (group mean) peak elbow load magnitude did not show a relationship with UCL injuries [1,2] and restrictions on solely the pitch number factor (i.e., pitch count) cannot prevent pitchers from injuries [3,4]. The stress-strain-dynamic capacity model shows the importance of the coherence of multiple factors, like frequency and load magnitude in relation to injury risk. This is in line with the non-linear in-vitro relationship between load magnitude and UCL failure [5]. UCL failure is usually investigated under a constant load in in-vitro studies. However, repetitive pitching is accompanied with variation in elbow load, both within and between pitchers. Thus, in addition to the commonly studied variables of load magnitude and frequency, it is crucial to also consider the impact of within-individual load variability on injury risk. There are two complicating factors in this injury model.

The first one is that the UCL load cannot be directly measured during pitching. The external valgus torque is used as a proxy, the interpretation of which is biased because it does not fully represent the UCL load, for instance, due to the stress-shielding effect of the elbow muscles. The second complicating factor is that pitching hundred balls in ten sets of ten, with rest in between, results in less stress on the body compared to pitching all hundred consecutively because of recovery. Recovery could have a positive effect on the elbow load magnitude, variability and stress shielding effect, and injury threshold. To conclude, the injury model shows the effect of the selected biomechanical variables as part of the injury mechanisms, while also the interaction between these biomechanical variables is important in relation to UCL injuries.

STRESS-STRAIN-DYNAMIC CAPACITY IN UCL INJURIES

We employed the stress-strain-dynamic capacity model to contextualize the various aims within the scope of UCL injuries in baseball pitchers (Figure 2). The stress-strain-dynamic capacity model describes how the sports environment results in (mechanical) loads on the athlete and considers the short and long-term (positive and negative) responses. Two biomechanical systems distinguish the boundaries between external exposure and internal exposure. Linked-segment models define the external exposure and musculoskeletal models are the system boundary of internal exposure.

EXTERNAL EXPOSURE

The external exposure is related to performance and injury risk (Figure 2). We showed that an increase in external valgus torque magnitude is related to ball speed (*Chapter 5)* but also to injury risk (*Chapters 4 & 5)*. Pitchers should strive to optimize the execution of their pitching movement (external exposure) to achieve the highest possible performance with the lowest injury risk.

Pitching mechanics

Pitching mechanics influence both ball speed and elbow load. The differences in elbow load magnitude between baseball pitchers can be explained by pitching mechanics and body anthropometrics. The elbow load magnitude is increased by the inertia in pitchers with a greater body segment mass and height. To reduce elbow load, changing pitchers' anthropometry is not possible, but improving their pitching mechanics can be achieved. In addition, the differences in within-individual elbow load variability between pitchers can solely

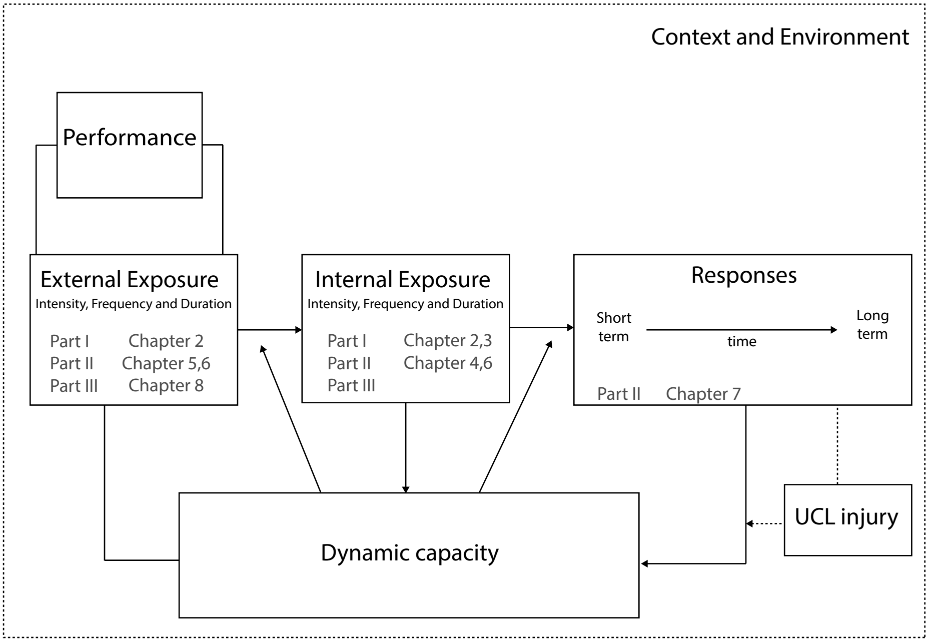

Figure 2. shows the stress-strain-dynamic capacity model including the chapters of this dissertation, in the context of elbow load in baseball pitching. In part I "the single pitch" the intensity (load magnitude) is investigated at the level of external exposure (the external valgus torque) and the internal exposure (muscle activation and UCL load). In part II "repetitive pitching" the focus is on the intensity and frequency at the level of external (external valgus torque) and internal exposure (muscle activity and UCL load) and short-term responses (UCL morphology and laxity). Part III is at the level of the external exposure as the intensity (external valgus torque) is predicted based on body kinematics.

be explained by differences in pitching mechanics. This is because inertia, body weight, and length do not change in linked segment models during a single pitching session.

The coordinated movement of the entire body in pitching is commonly referred to as a single kinetic chain, also known as the summation of speed principle [6]. In this principle, each body segment starts rotating at the moment of the adjacent segment's peak angular velocity up in the chain. It has been hypothesized that a breakdown in the chain alters forces in the more distally located segments leading to increased elbow load and possible injuries, described as the catch-up phenomenon [7]. Recently, we showed that an experimentally decreased pelvis-trunk separation time (by impeding the mobility of the connection between pelvis and trunk) within individuals did not influence elbow load and almost not ball speed [8]. This is contradictory to the catch-up phenomenon and the summation of speed principle. The pitchers compensated with an increase in peak pelvis angular velocity, indicating pitching toward the direction of the so-called principle of optimal coordination of partial momenta

[6]. The principle of optimal coordination of partial momenta suggests that each segment reaches peak angular velocity at the same time. Similar conclusions can be drawn from *Chapter 8* where we observed high predictive performance of statistical models for elbow load, including the pelvis and trunk peak angular velocity but less predictive performance for the pelvis-trunk separation time (*Chapter 8)*. That pitchers are not throwing via one of the two principles is also seen within pitchers, no consistent sequence of peak angular velocities (pelvis, trunk, upper arm, forearm, and hand) was found within 90% of these pitchers [9]. Among all pitchers, the peak angular velocities of the throwing arm consistently occurred later than that of the pelvis and trunk, but different sequences are reported within the pelvis trunk region and the throwing arm region [9].

Both partial momenta and summation of speed principle assume that energy is generated and transferred from the lower extremity up to the ball. However, these principles do not explain whether and where the energy is generated and/or transferred. Energy flow analysis can reveal the generation and absorption of energy by muscles around the joint and the transfer of energy between body segments. Understanding this energy flow can help to understand to optimize energy delivery and reduce elbow load [10,11]. We showed that the legs contribute differently to the energy flow [12]. The leading leg transfers energy in a distal-to-proximal order like an initial kinetic chain. The trailing leg, better called the driving leg, was mainly generating energy and showed energy transfer but not in a distal-to-proximal order [12]. The energy from both legs comes together in the pelvis and is transferred up to the trunk. Aguinaldo et al. (2019) found that the segmental trunk power is positively related to the external valgus torque [13]. This is in line with *Chapter 8,* where we found that trunk peak angular velocity is a good predictor for elbow load. Future research should investigate whether energy transfer or generation/absorption is related to elbow load and if pitchers with a more efficient energy flow produce less elbow load.

In this dissertation, we solely investigated fastball pitches as external exposure to outwit a batter. However breaking balls, like curveballs, changeups, sliders, knuckleballs, and screwballs can also be used. Breaking balls typically show differences in body kinematics, e.g. lower pelvis and trunk peak angular velocities [14,15]. Breaking balls typically involve a lower level of elbow valgus torque and lower ball speeds compared to fastball pitching [15,16].

To conclude, the observed differences between and within pitcher elbow load (*Chapters 5 and 6)* can be explained by differences in pitching mechanics. However, it is too simplistic to explain this by a single kinetic chain that follows the summation of speed principle. Therefore, to understand how pitching mechanics influence elbow load, we propose that there is an overarching kinetic chain that follows the kinematic sequence order from the lower extremities up to the pelvis-trunk region followed by the throwing arm. This overarching kinetic chain contains smaller kinetic chains (see the colors in Figure 3) that can behave either via the summation of speed principle or the optimal coordination of partial momenta.

Variations in sequence and segment peak angular velocities in these smaller kinetic chains between and within pitchers influence the elbow load. Future research should determine how the intersegmental timing, angular velocities, and energy flow of the overarching and smaller kinetic chains are related to elbow load.

Figure 3. shows the overarching kinetic chain, the colors show the smaller kinetic chains of the leading leg, pelvis trunk region, and the throwing arm.

Elbow load magnitude and variability within and between pitching sessions

It can be assumed that the optimal balance between performance and injury risk is changing between sessions. Pitchers are not performing constantly within and between sessions and pitchers show individual alterations in elbow load magnitude and variability during a session *(Chapter 6)*. Thus, knowledge about the elbow load during a single session is not representative over a longer period. On a group level, it is for example known that the load magnitude increases in the development phase [17], but no significant differences were found in load variability on the group level between levels of play [18]. The long-term effect of pitching on the elbow load during pitching is unknown on both group levels and within individuals. The injury model shows that an increase in within individual elbow load magnitude and variability are related to injury risk. These individual alterations cannot be detected when investigating the elbow load magnitude and variability on a group level. For this, within session variability in elbow load magnitude should be continuously monitored for each individual pitcher.

To highlight the importance of monitoring within-individual pitching session variation in elbow load between sessions over seasons we simulated the individual pitcher elbow load data based on the current biomechanical knowledge. With the assumption of multiple pitching days and rest days for a pitcher, a session distribution of elbow loads within a month can be established (Figure 4A). The combination of rest days between pitching sessions and the elbow load magnitude and variability is likely to be an important factor. Insufficient recovery time could lead to an increase in elbow load magnitude and variability as a result of fatigue, potentially caused by changes in pitching mechanics. In Figure 4B we show the assumed monthly individual pitcher elbow load distribution over a year, quantified from the monthly single sessions. Our hypothesis is that over the course of the season from April to September, the magnitude of elbow load increases due to alterations in pitching mechanics. The offseason starts in October with rest and in November pitchers start to gradually increase their pitching effort. It can, therefore, not be assumed that the individual elbow load magnitude and variability are constant during sessions and over seasons. The time between pitches within a session and the days between sessions is an important factor as insufficient between pitch or between pitch session time is related to fatigue and sufficient time is related to recovery. Future research should thus focus on monitoring elbow loads within individual pitchers within sessions and for multiple seasons.

INTERNAL EXPOSURE

It is not possible to quantify the UCL load directly during pitching. Musculoskeletal models enable the estimation of UCL load during pitching without the need for invasive methods. These models should consider coherence and mechanical action between the elbow structural and functional stabilizers when quantifying the UCL load from the elbow load external exposure (*Chapters 2 & 3*). The benefit of musculoskeletal models compared to the used linked segments models for external exposure is that they are not restricted to modeling the elbow joint as a hinge joint and include muscles, ligaments, and joint geometry.

Stress shielding

The elbow muscles and the joint articulations are important in maintaining elbow joint integrity and thus in shielding the UCL from high loads (*Chapters 2 & 3*). The flexor pronator muscles have large moment arms with the varus-valgus axis [19] and are thus able to directly and effectively counteract the external valgus torque that is observed during the late cocking phase in the baseball pitch. The biceps and triceps muscles have much smaller moments

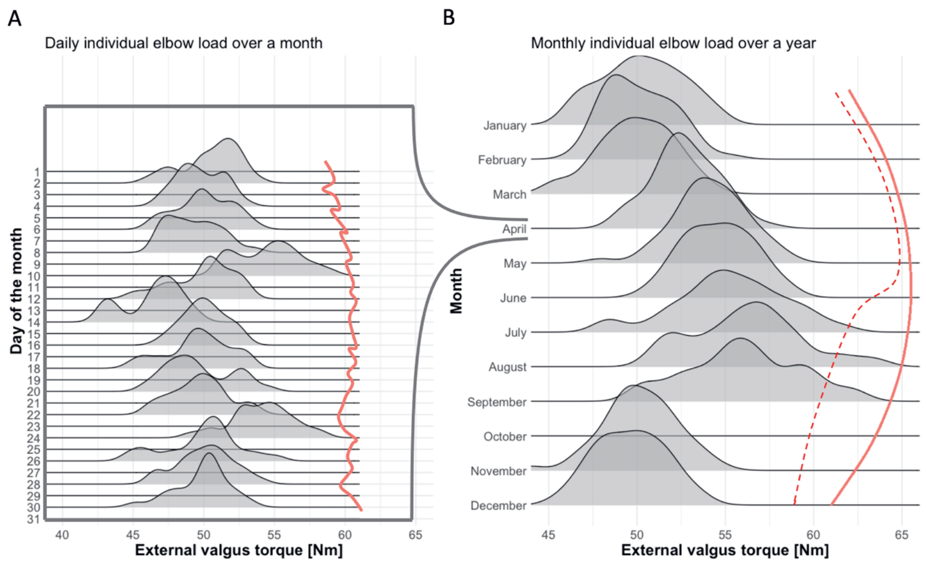

Figure 4. shows simulated external valgus torque data of an individual pitcher. Panel A shows the elbow load magnitude and variability over different sessions within a month. Panel B shows the elbow load magnitude and variability over a whole season. The red line represents the injury threshold.

arms with the varus-valgus axis [19]. Thus, they are less efficient to counteract the external valgus torque. However, high levels of co-contraction of the biceps and triceps in combination with the joint geometry can maintain elbow joint integrity. A dynamic musculoskeletal model including the biceps, triceps, and brachialis muscles showed that the elbow joint contact pressure increased with velocity during a simple flexion-extension task [20]. Thus, examining the stress shielding function of co-contraction of the biceps and triceps should be considered in combination with joint geometry, because changes or individual differences in joint geometry influence the stabilization effect of the biceps-triceps co-contraction and thus UCL loading. The influence of joint geometry is reported in the study of Paul et al. (2023) who found that most pitchers returned to play successfully after the removal of posteromedial osteophyte resection, although they showed a higher risk of UCL reconstructions.

Muscle morphology differs between pitchers, for example with respect to fiber types and cross-sectional areas of relevant muscle groups. In addition, elbow muscle recruitment patterns are various among pitchers during pitching (*Chapter 3, appendix)*, and in relation to repetitive pitching individual differences are found in elbow muscle activity between pitchers (*Chapter 6)*. A larger flexor pronator mass volume, with the same level of activation, produces more force and might be better at shielding the UCL. Thus, the stress shielding is different between pitchers which will influence the UCL load.

In the present dissertation we investigated the stress shielding effect of the elbow muscles on UCL loading in fastball pitches. However, for other pitch types stress shielding around the elbow could be different. Although the elbow flexion-extension angle is similar between pitch types [21], the rotation of the forearm differs between pitch types. For curve balls the forearm is supinated from foot contact until ball release, whereas in fastball pitching it is pronated [16]. The supinated forearm could disable the function of the flexor-pronator mass muscles, thus reducing the stress shielding in curve balls. Interestingly is that the biceps brachii muscle, which has a supination function, is less active during a curve ball compared to fastball pitches at MER [22]. So, the lower external valgus torques in breaking ball pitches do not directly indicate lower UCL load because of the differences in the forearm positions and the flexor-pronator mass' shielding effect between fastball and breaking ball pitches. Future studies should further investigate elbow muscle stress shielding in relation to different pitch types because a reduction in stress shielding increases the UCL load and thus injury risk.

The stress shielding effect of elbow muscles can be thought of as a protection mechanism and thus could prevent athletes from UCL injuries. Baseball pitching requires optimal elbow muscle force to counteract the external valgus torque to protect the UCL from high loads. Therefore, strength and coordination training of the elbow muscles is important. Harada et al. (2010) did not find a relationship between maximal handgrip force and UCL injuries. The maximal handgrip force on itself might not be an important factor. In such a fast movement as pitching, it is likely more important that muscle force is produced fast than at high maximum values. Thus, the rate of force development may be important which requires explosive strength training [23]. In addition, also endurance strength training is needed as we found alterations in muscle activation in individuals with repetitive pitching (*Chapter 6)*. Variations in elbow muscle activation within and between pitchers were found at the critical elbow load (*Chapter 3)*. A delayed or lower muscle activation at the critical elbow load reduces stress shielding. It is essential to deliver the optimal force at the right moment during pitching. Therefore, to optimize muscle stress shielding, explosive and endurance strength training should be combined with coordination training.

Stress shielding within and between pitching sessions

UCL stress shielding by elbow muscle activity in baseball pitching can change within pitching sessions and be different between sessions. A computer model developed by Sonne & Keir (2016) showed that a decrease in time between pitches during a simulated baseball game increased muscle fatigue, showing a potentially within session change in UCL stress shielding. In addition, we reported in *Chapter 6* individual differences in muscle activation within a session. Both results indicate that the shielding effect cannot be considered constant within and between pitching sessions. Between sessions, time is also an important variable because muscles need to recover after an exercise to adapt positively. Potteiger et al. (1992) showed that creatine kinase and lactate dehydrogenase (muscle damage biomarkers) peaked after 6 to 24 hours of exercise and with baseline levels returning within 48 to 72 hours [24]. Fully recovered muscles can function optimally and produce optimal force. However, if muscles are not recovered because of a lack of recovery time, negative adaptation may occur, and the muscles might produce less force resulting in a decrease in stress shielding.

Monitoring muscle activity with EMG over time is likely the most appropriate method for quantifying the within and between-session shielding effect in relation to UCL injuries. EMG is a noisy signal, and factors such as electrode placement, skin preparation, and the level of muscle activity can all affect the reliability of EMG measurements over time. The between-session reliability of biceps and triceps EMG ranged from good to excellent (ICC 0.75-0.98) for closed kinetic chain exercises on a stable surface [25]. However, in exercises on a flexible surface the ICCs of biceps and triceps muscle activity values were lower (ICC 0.14-0.85), although most of the exercises were accompanied with good to excellent ICCs. These results are promising, but static and closed kinetic chain exercises cannot be compared to the highly dynamic and open kinetic chain motion of baseball pitching. It is essential to examine the intersession reliability of EMG measurements in pitching in the future, which subsequently can be used to monitor and identify changes in the stress shielding that may be associated with UCL injuries.

SHORT-TERM AND LONG-TERM RESPONSES

The UCL injury threshold adapts positively or negatively to stress. Directly after repetitive pitching, the adaptation will probably be negative, although we did not find (positive or negative) short-term responses in the UCL morphology and humeroulnar joint gap directly after a repetitive pitching session (*Chapter 7)*. It is possible that we were not able to detect a short-term response if the negative response happened on a microscopic level (Figure 5A, linear region). An in-situ study on the anterior cruciate ligament showed microdamage during and after submaximal loading [26]. Comparable microdamage in the UCL morphology cannot be detected with ultrasound. However, changes in the ligament morphology might become visible after a few hours or a few days as an inflammatory reaction might thicken the ligament [27]. The long-term response of pitching shows changes during the season in UCL thickness and humeroulnar joint gap in pitchers [28]. Whether these changes reflect an increase in UCL strength or an inflammatory and thus a decrease in UCL strength (i.e., a decrease in the injury threshold) is yet unknown. We assume that the UCL injury threshold is not constant during a season. The red line in Figure 4B shows the assumed injury threshold for an asymptomatic pitcher. As a result of UCL loading and optimal recovery, the injury threshold is expected to increase during in-season (April-September). During off-season, the injury threshold will probably decrease because of decreased mechanical exposure to pitching. Furthermore, this threshold can be different for individuals during a season. An individual that does not consider enough rest could show a decreased injury threshold during the in season (red dashed line in Figure 4B).

Determining the injury threshold

In the search of information about the individual injury threshold, knowledge about the properties of the UCL is of interest. From a mechanical perspective, the material failure can be explained by a stress-strain curve (Figure 5). This curve contains a toe region, a linear region, and a failure point for collagen, which is the structure of a ligament (Figure 5A). The slope of the linear region is referred to as the Young modulus of the ligament [27]. Stress is equal to the force divided by the structure's cross-sectional area. The strain is the optimal length of the structure divided by the measured length. Information about the stress-strain curve for the UCL would provide information about the individual injury threshold.

The measurement setup in *Chapter 7* provides information about individual young's modulus. Ideally, we would use the UCL length for the strain, but ultrasound images in *Chapter 7* did not show changes in UCL length with applied valgus stress, but the humeroulnar joint gap did and can be assumed as a proxy for the UCL strain. The strain (ε) can be calculated by equation 2. Where l is the humeroulnar joint gap at the applied valgus stress of 50N and 100N and l0 is the humerulnar joint gap at rest (0N). The stress (σ) can be calculated by the applied valgus force divided by the UCL's cross-sectional area (Equation 1). The cross-sectional area can be assumed as the UCL thickness (*Chapter 7; Figure 1*) multiplied by the depth of the UCL. The UCL depth cannot be quantified with ultrasound therefore we assumed it as a constant factor of 2 mm. With this, the cross-sectional area agreed with the specimens' cross-sectional area of 12.94 mm^2 in de study of Regan et al. (1993).

$$\sigma = \frac{F\ valgus}{UCL\ thickness * 2}$$ (Equation 1)

$$\varepsilon = \frac{l - l0}{l0}$$ (Equation 2)

Figure 5B shows the linear region of the stress-strain curves for each pitcher measured in *Chapter 7*. The slope, or estimated Young's modulus value, is different between pitchers (Figure 5B). Further investigation is needed to determine if this information can be used to calculate the ultimate UCL load, as these lines provide insight into the linear region. A steeper slope suggests a stiffer material and a flatter slope laxer material. This suggests that UCL properties vary among individuals, likely leading to individualized thresholds.

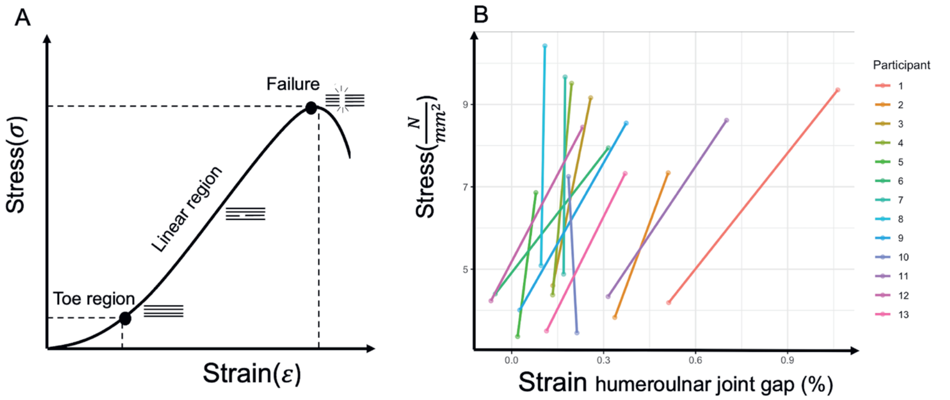

Figure 5. Panel A shows the stress-strain curve for collagen material like a ligament. Panel B shows the linear region of the stress-strain relationship of each participant measured in chapter 7. The x-axis is the stress the applied valgus stress divided by the UCL cross sectional area. The y-axis shows the strain of the humeroulnar joint gap.

PREVENTING INJURIES WITH DATA-DRIVEN SENSORS AND REAL-TIME FEEDBACK

In search of preventing baseball pitchers from UCL injuries, it is important to quantify the pitch number, the within-individual elbow load magnitude and variability, and the shielding effect of elbow muscle activity. Ideally, we should also follow these key variables over time, both short-term (within session) as long-term (within season). We formulated the following initial requirements for the development of an "early warning system" based on the selected biomechanical variables:

1) Count the number of pitches during training or game.
2) Quantify individual elbow load in the field during pitching.
3) Quantify the time between pitches and between sessions.
4) Quantify the shielding effect of elbow muscles during pitching.
5) Provide the pitcher with feedback about elbow load.
6) Predict elbow injury risk.

In part III of this dissertation, we started with quantifying the elbow load based on easy-to-measure body kinematic parameters in the field. The knowledge obtained in *part II* about the within-individual load variability of pitchers was included in the prediction of elbow load based on pelvis and trunk angular velocities. Elbow load predictions were excellent because of the inclusion of individual data *(Chapter 8).* These analyses were performed with motion capture data, but with the rationale that pelvis and trunk peak angular velocities are easy to measure with wearable inertial measurement unit sensors in the field.

Wearable sensor systems offer practical advantages over (marker-based) motion capture systems, as they can be easily applied with no restrictions on capture volume and are less time-consuming. Wearable sensors allow for continuous monitoring of biomechanical parameters and thus seem interesting for monitoring the elbow load of every pitch in each pitcher over a longer period. The PitchPerfect system, developed in the FASTBALL project [29], is a wearable system that measures the peak pelvis and trunk angular velocities based on the gyroscope data in IMUs. Implementing the prediction model in the PitchPerfect system can provide the pitcher with information about their elbow load. Based on the peak angular velocities it is possible for the PitchPerfect system to count the number and frequency of pitches. A timestamp of each pitch and each session gives information about the time within a session and between sessions. This satisfies the initial requirements 1, 2 & 3.

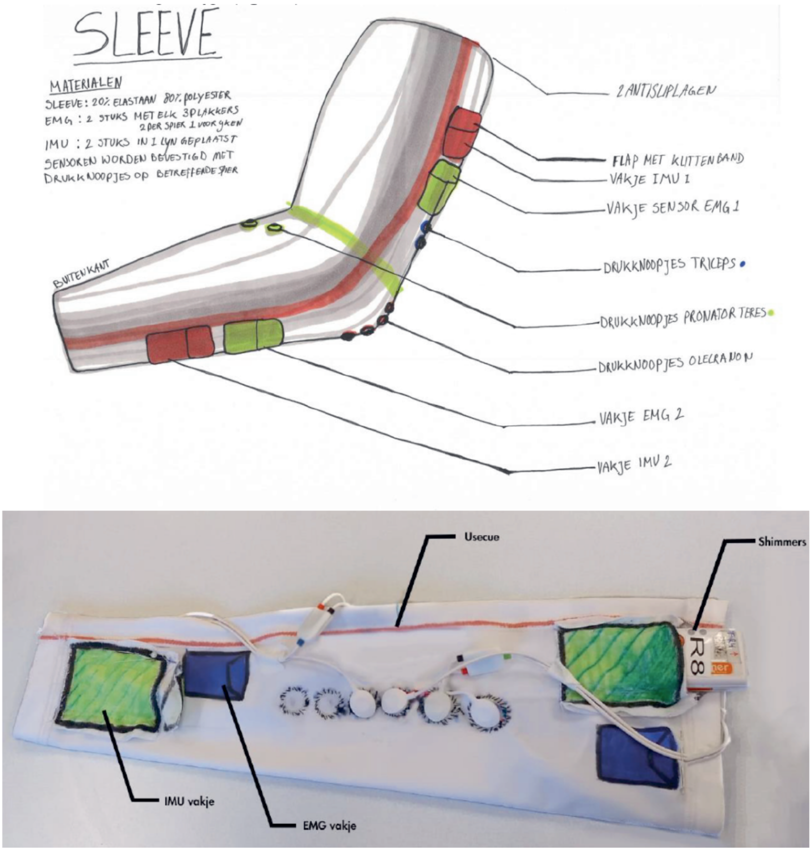

Figure 6. our developed prototype of a sleeve to measure EMG in the field.

For the initial requirement of quantifying the shielding effect of elbow muscles, electromyography of the elbow muscles must be established in the field. The measurements in *Chapters 3 & 6* were performed with the PLUX portable measurement system (Plux biosignals, Arruda dos Vinhos, Portugal). The portable use of EMG shows the rapid development of sensor technology; however, it was still time-consuming to attach the wet electrodes and wires. To save time, we made a prototype of a sleeve with the PLUX device including dry electrodes (Figure 6). Dry electrodes are developed and show promising results for wearable devices [30]. This sleeve's final design should not include wires and not a bulky but a small EMG device.

After fulfilling the first four requirements, the fifth requirement in the development of an early warning system for UCL overload in baseball pitching can be met by providing pitchers or coaches with visual feedback about the pitchers' elbow load magnitude and variability, pitch count, and forearm muscle activations. The visualization should focus on the elbow load magnitude and consistency. In addition, changes in elbow load magnitude and variability should be highlighted as a warning for possible injury risk. The next step is to investigate if the provided feedback does have a positive effect on the reduction of elbow injuries in the future. Figure 7 shows an example of visual feedback to the pitchers on a pitch count and elbow load magnitude and variability in training.

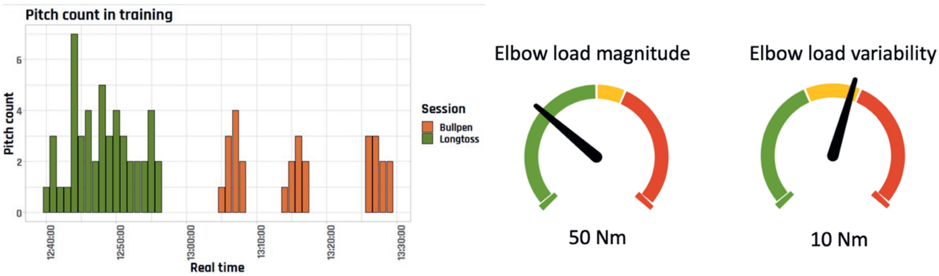

Figure 7. Visualization of pitch count over time during a training session and the average elbow load magnitude and variability of a training session.

The sixth, and most difficult, requirement is the prediction of elbow injury risk. With the longitudinal FASTBALL dataset we tried to predict elbow injuries with range of motion, muscle force, ball speed, and training duration data, measured twice per year, over three years [31]. Different statistical models showed low prediction results. We concluded that more frequent measurement data and biomechanical data were needed to predict elbow injuries [31]. Hence, to predict elbow injury risk in baseball pitching, large datasets containing the elbow load and elbow muscle activity as predictors, and elbow injuries as outcome variable, over an extended period of time are needed. It is complex and time-consuming to develop such a research setting. Therefore, a collaboration between universities, baseball teams, and companies is key to investigate the relationship between elbow load and UCL injuries and subsequently to develop an “early warning system”. The commercialization of wearable sensors by companies makes it possible to quantify individual biomechanical data on a large scale in the field. Baseball teams can use these sensors to gain knowledge about the pitchers’ load and performance. By utilizing longitudinal prospective data, universities can investigate the elbow load (on the intensity dimension of external exposure) in relation to the dynamic capacity of the pitcher to arrive at maximal performance with minimal injury risk. This analysis can help validate the injury model.

In a recent implementation project, we (the university) are working together with the PitchPerfect company and the Royal Dutch Baseball and Softball Federation (KNBSB). The experiences gained in this project showed that it is important for all parties involved to be committed and to work together towards a common goal. It is important to be aware of the (obvious) barriers and facilitators of implementation and develop strategies to overcome these barriers [32,33].

THE INJURY MODEL IN OTHER (OVERHEAD) SPORTS

The knowledge obtained in this dissertation can be of value for other (overhead) sports. Baseball pitching is the leader in providing sports-related UCL injuries, but they are also reported in overhead athletes who participate in javelin throwing, softball, tennis, badminton, and water polo [34–38]. The overhead projectile motions in these sports are based on the same fundamental movements as baseball pitching, like the summation of speed principle and the principle of optimal coordination of partial momenta [39,40]. Similar elbow loads are reported as in pitching (Table 1). In these sports, the elbow muscles can probably also shield the UCL from the high external valgus torques. Indeed, during the tennis serve high levels of muscle activation in the flexor pronator mass and triceps, and low muscle activation of the biceps activity, are reported during the arm cocking and acceleration phases [41]. Interestingly, fewer UCL injuries are reported in tennis compared to baseball, while the elbow load is similar (Table 1). It is possible that holding the tennis racket activates the elbow muscles more constantly and thus automatically provides a better shielding effect. Investigating the effect of elbow muscle activity in other overhead sports, like tennis, would be interesting to further investigate stress shielding, as it can prevent athletes from UCL injuries. However, we should not focus exclusively on the shielding effect as the differences in reported injuries could also be explained by kinematic differences or other (external) exposure factors (i.e. frequency and intensity).

Table 1. The external valgus torque in other overhead sports movements for male and female athletes.

Sport (movement)	External valgus torque (Nm)		Level or age	Study
	Male	**Female**		
Tennis (Serve)	78.3 (SD12.2)	58.2 (SD 13.1)	Professionals	Elliot et al. (2003)
Javelin throwing	88 (SD 31)		23 (range 15-48) years	Leigh et al. (2012)
Softball		50.4 (SD 19.5)	21 (SD 4) years	Barrentine et al. (1998)
Volleyball (Jump serve)		43.3 (SD 10.6)	Collegiate 21 (SD 2) years	Reeser et al. (2010)

The developed injury model shows its potential in other overhead sports. The elbow load magnitude, variability, stress shielding, and the effect of fatigue and recovery are also present in these sports. Next to these variables, the framework of the stress-strain-dynamic capacity model can be used to structure and select exposure variables related to frequency, intensity, and duration. In baseball pitching, for example, the duration (of a match) is less important, but in tennis the duration becomes important in for instance the length of rallies and matches.

CONCLUSIONS AND RECOMMENDATIONS

In search of answers on the origin of UCL and elbow injuries, it can be concluded that we should focus specifically on the collaboration and mechanical interaction between the elbow's structural and functional stabilizers. To understand why one pitcher sustains an elbow injury and another does not, it can be concluded that solely focusing on a single biomechanical factor cannot explain overuse injuries. We should focus more on within-individual load variability and the influence of individual load magnitude and variability while pitching repetitively. Furthermore, the stabilizing function of the muscles cannot be considered constant within an individual while pitching repetitively, which influences the UCL load magnitude and variability. Thus, to prevent pitchers from elbow injuries it is necessary to quantify both the frequency (pitch number) and intensity (elbow load) dimensions of the external exposure. A prediction model that combines group and individual data can predict individual elbow load by the rotations of their pelvis and trunk during pitching. The discovered injury mechanisms in this dissertation showed the importance of individual elbow load in baseball pitchers and how it can be monitored in the field. Pelvis and trunk wearable sensors can be used to monitor individual elbow load and the development of an "early warning feedback system" might prevent athletes from overuse injuries in the future.

Practical recommendations

The following practical recommendations are formulated for clinicians, coaches, and pitchers:

- Elbow muscle training might well work to protect the UCL from high loads, it is important to train the elbow muscles in strength and coordination. Coordination is particularly crucial as delayed muscle activation can increase UCL load.
- Although likely effective as a preventive measure, quantifying pitch count alone is too much of a “one size fits all” measure. Individual variables related to technique can and should also be included.
- Preventive measures need to be individualized: variations in elbow load and elbow muscle activity between pitchers become apparent during repetitive pitching.
- To reduce elbow load, we should take into account full-body pitching mechanics. The “proper” use of the lower extremities and pelvis trunk region can reduce the elbow load. Wearable commercial sensors which measure body kinematics can be used in the future to provide insights into pitching mechanics and thus elbow load.
- Collecting information about the state of the UCL over a longer period by measuring the UCL thickness and humeroulnar joint gap (using ultra-sound) is more beneficial in relation to UCL injuries than immediately after a single pitching session.
- The individual differences in elbow load magnitude and variability and muscle activation levels in baseball pitching should be considered in the return-to-sports programs after a UCL reconstruction. These programs should not solely be based on a pitch count but should also include information about the individual elbow load and muscle activation levels.

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Hoe gaat het nu verder?
Een pitcher, embedded scientist en fysiotherapeut vertellen.

APPENDICES

Summary

Samenvatting

Acknowledgments

PhD portfolio

List of Publications

SUMMARY

In baseball pitching, high performance is closely related to injuries. The baseball pitch is a rapid, full-body throwing motion that culminates in a ballistic motion of the throwing arm, creating high ball velocity but exposing the elbow to significant loads. As a result, injuries to the medial side of the elbow involving the Ulnar Collateral Ligament (UCL) are currently a major concern in baseball pitchers at all levels of play. UCL injuries are recently prevalent among youth pitchers and injury rates have gradually increased over the years. It is important to prevent injuries in (youth) pitchers, not only to attain healthy pitching performance but also to avoid injuries at older ages. The general aim underlying the present dissertation is to establish biomechanical injury mechanisms related to the Ulnar Collateral Ligament in baseball pitchers. Knowledge of these mechanisms can eventually be used to develop an 'early warning system' to safeguard baseball pitchers from UCL injuries. This dissertation is divided into three parts.

The single pitch

In the first part, we aim to describe the relationship between the UCL properties and elbow stabilizers with the UCL loading during pitching. The elbow load during pitching is approximately 5Nm to 85Nm higher than the ultimate in-vitro (cadaver) UCL torque. This mismatch raises the question of why not every UCL is torn during a single pitch and thus why 'only' 16% of the pitchers sustain a UCL injury (Chapter 2). Underestimation of the effect of other structures in in-vivo studies is the most likely explanation for this mismatch because the calculated in-vivo external valgus torque also includes possible contributions of functional and structural stabilizers. The elbow muscles (functional stabilizers) show activity at the critical instant of elbow loading during pitching (Chapter 3). We conclude that the elbow muscles are important in shielding the UCL (structural stabilizer) during pitching and should be included when quantifying the UCL load.

Repetitive pitching

In the second part, we investigated the effect of repetitive pitching in relation to elbow load. The central question was: Why does one pitcher sustain a UCL injury, and another does not? A simple explanatory injury model was developed to illustrate the relationship between within-individual load variability and injury risk, illustrating how pitchers with a higher load variability are more likely to sustain an injury compared to pitchers with less load variability (Chapter 4). In addition, this model shows that all pitchers are at risk of sustaining an injury; higher load variability, higher magnitude, and longer exposure all increase this risk. Furthermore, the model comprises the (theoretical) effect of fatigue on load variability and injury threshold

over time. Measuring the exact UCL loading during pitching is complex if not impossible. At this point, the external valgus torque is likely the best proxy to quantify medial elbow load and thus indirectly UCL load. The within-individual external valgus torque variability shows differences across elite baseball pitchers (Chapter 5). The presence of, and differences in, within-individual elbow load variability among baseball pitchers seems, in addition to the load magnitude, an important variable in injury assessment and possibly in injury prevention. Subsequently, we investigated whether there is a change in within-individual load magnitude and variability as an effect of repetitive pitching due to musculoskeletal fatigue-related kinematic changes during pitching (Chapter 6). The elbow within-individual load magnitude and variability differ significantly among pitchers with repetitive pitching. This could explain why repetitive pitching was not significantly related to elbow load at group level. From the gained knowledge in part I we intended to determine if and how repetitive pitching affects the activation of the elbow muscles during pitching. Repetitive pitching showed significant variations in muscle activation among pitchers. This indicates that the shielding effect of elbow muscles cannot be considered a constant variable. Repetitive high elbow loads can lead to positive or negative UCL adaptations, influencing the injury threshold. Therefore, the short-term UCL response to elbow stress was investigated. Higher static applied valgus stress increases the humeroulnar joint gap, although, a single session of repetitive pitching did not influence the UCL morphology and the humeroulnar joint gap. The contribution of handgrip force, reflecting the forearm muscle force and shielding effect, did not affect the humeroulnar joint gap for different levels of elbow valgus stress after repetitive pitching compared to before repetitive pitching (Chapter 7). Thus, next to the elbow load magnitude, it is important to consider the within-individual elbow load variability and its individual trajectory with repetitive pitching. The individual muscle activation trajectory is influenced by repetitive pitching shows the importance of individual differences while repetitive pitching.

Preventing injuries with data-driven sensors and real-time feedback

In the third part, we investigate if we could predict the external valgus torque in the field based on body kinematics (Chapter 8). With the use of data science, the results show that it is possible to predict individual elbow load based on the trunk peak angular velocity and the separation time between the peak angular velocities of the pelvis and trunk. An excellent prediction was only possible with a hierarchical linear model, which includes an individual level in addition to the group level. Thus, quantifying the individual elbow load in the field is possible with the condition that the prediction is a mix between group and individual levels.

This dissertation finalizes with a general discussion (Chapter 9), in which we reflect on the process of reaching the overall aim, methodological considerations, the application, and future directions. In search of answers on the origin of UCL and elbow injuries, it can be concluded that we should focus specifically on the collaboration and mechanical interaction between the elbow's structural and functional stabilizers. In addition, we should consider the elbow load magnitude and its variability in relation to repetitive pitching within an individual. For injury assessment and prevention, it is essential to quantify the individual elbow/UCL load (intensity) next to the pitch count (frequency). To prevent pitchers from injuries in the future it is important to monitor the elbow load frequency and intensity in the field. This is possible by monitoring the elbow load with wearable sensors placed on the pelvis and trunk during each training and game. Longitudinal data will provide new individual information about alterations in elbow load (magnitude and variability) and recovery which might be related to overuse injuries. In addition, pelvis and trunk kinematics and intersegmental timing are important in relation to performance. Thus, monitoring these variables by measuring the pelvis and trunk kinematics with wearable sensors can be used to develop an "early warning system" to prevent athletes from overuse injuries and at the same time provide real-time feedback to improve pitching performance.

SAMENVATTING

In honkbal is de uitvoering van de worp hoog gerelateerd aan blessures. De honkbalworp is een snelle beweging van het gehele lichaam. Het is ballistische beweging van de werparm, wat resulteert in een hoge balsnelheid maar ook in een grote belasting op de elleboog. Blessures aan de mediale zijde van de elleboog, o.a. aan het ulnaire collaterale ligament (UCL), zijn momenteel een groot probleem bij honkbalwerpers op alle spelniveaus. Daarnaast komen UCL-blessures tegenwoordig ook vaker voor bij jeugdwerpers. Blessures zijn in de loop der jaren geleidelijk toegenomen. Het is belangrijk om blessures bij (jeugd)werpers te voorkomen, niet alleen om een gezonde werpprestatie te bereiken, maar ook om de kans op blessures op latere leeftijd te verminderen. Het algemene doel van dit proefschrift is het vaststellen van biomechanische blessuremechanismen die verband houden met het ulnaire collaterale ligament bij honkbalwerpers. Kennis van deze mechanismen kan uiteindelijk worden gebruikt om een 'vroegtijdig waarschuwingssysteem' te ontwikkelen om honkbalwerpers te beschermen tegen elleboog en UCL-blessures. Dit proefschrift is verdeeld in drie delen.

De enkele worp

In het eerste deel beogen we de relatie te beschrijven tussen de eigenschappen van het UCL en de stabilisatoren van de elleboog met de belasting van het UCL tijdens het werpen. De belasting van de elleboog tijdens het werpen is ongeveer 5 tot 85 Nm hoger dan het maximale moment van het UCL in-vitro (kadaver). Deze discrepantie roept de vraag op waarom werpers niet bij één enkele worp hun UCL afscheuren. Of te wel waarom loopt dan 'slechts' 16% van de werpers een UCL-blessure op (Hoofdstuk 2). Onderschatting van het effect van andere structuren in in-vivo studies is de meest waarschijnlijke verklaring voor deze discrepantie. Omdat het in-vivo externe valgus moment mogelijk ook wordt tegengegaan door dynamische stabilisatoren. De elleboogspieren (dynamische stabilisatoren) vertonen activiteit op het kritieke moment van de elleboogbelasting tijdens het werpen (Hoofdstuk 3). Hieruit valt te concluderen dat de elleboogspieren belangrijk zijn om het UCL (structurele stabilisator) tijdens het werpen te beschermen. Bij het kwantificeren van de belasting van het UCL gedurende een worp is het dus van belang het stabiliserende effect van de elleboogspieren mee te nemen.

Herhaaldelijk werpen

In het tweede deel hebben we het effect van herhaaldelijk werpen in relatie tot elleboogbelasting onderzocht. De centrale vraag was: Waarom loopt de ene werper een UCL-blessure op en de andere niet? Er is een eenvoudig verklarend blessuremodel ontwikkeld om de relatie tussen variabiliteit in belasting binnen het individu en het risico op blessures te illustreren. Daarbij wordt aangetoond dat werpers met een hogere variabiliteit in belasting een grotere kans hebben om een blessure te krijgen dan werpers met een lagere variabiliteit in belasting (Hoofdstuk 4). Bovendien toont dit model aan dat alle werpers het risico lopen om geblesseerd te raken; hogere variabiliteit in belasting, toenemende grote in belasting en langere blootstelling verhogen het blessurerisico. Het model omvat ook het (theoretische) effect van vermoeidheid op variabiliteit in belasting en de drempel voor blessures in de loop van de tijd. Het exact meten van de belasting op het UCL tijdens het werpen is complex, zo niet onmogelijk. De beste mogelijkheid om de mediale elleboogbelasting te kwantificeren is het externe valgus moment en daarmee indirect de belasting op het UCL. Het externe valgus moment binnen het individu vertoont verschillen tussen elite honkbalwerpers (Hoofdstuk 5). De aanwezigheid van variabiliteit in de belasting van de elleboog binnen het individu, en de verschillen daarin tussen werpers, lijkt naast de grote van de belasting een belangrijke variabele te zijn bij blessures en mogelijk bij blessurepreventie. Vermoeidheid gerelateerde kinematische verandering ontstaan als gevolg van herhaaldelijk werpen. Daarom hebben we onderzocht of er veranderingen zijn in de grote en variabiliteit van de elleboogbelasting binnen het individu als gevolg van herhaaldelijk werpen (Hoofdstuk 6). De grote en variabiliteit van de elleboogbelasting binnen het individu verschillen aanzienlijk tussen werpers die herhaaldelijk werpen. Dit zou kunnen verklaren waarom herhaaldelijk werpen op groepsniveau niet significant gerelateerd was aan de elleboogbelasting. Herhaaldelijk werpen vertoonde significante variaties in spieractivatie rondom de elleboog tussen werpers. Dit geeft aan dat het beschermende effect van elleboogspieren (Deel 1) niet als een constante variabele kan worden beschouwd. Herhaaldelijk hoge belasting aan de elleboog kan leiden tot positieve of negatieve aanpassingen van het UCL, wat de blessuredrempel beïnvloedt. Om inzichten te krijgen in deze drempel hebben we de korte termijn reactie van het UCL op statische elleboog stress onderzocht. Een hogere statische valgus belasting vergroot de opening van het humeroulnaire gewricht, hoewel een sessie van herhaaldelijk werpen de morfologie van het UCL en de opening van het humeroulnaire gewricht niet beïnvloedde. De bijdrage van handgreepkracht, die de kracht van de onderarmspieren en het beschermende effect weerspiegelt, had geen invloed op de opening van het humeroulnaire gewricht bij verschillende niveaus van valgus belasting na herhaaldelijk werpen in vergelijking met voor herhaaldelijk werpen (Hoofdstuk 7).

Het verminderen van blessures met sensortechnologie

In het derde deel is onderzocht of het externe valgus moment op het veld kan worden gemonitord op basis van lichaamskinematica (Hoofdstuk 8). Met behulp van voorspellende statistische modellen laten de resultaten zien dat het mogelijk is om individuele elleboogbelasting te voorspellen op basis van de piekhoeksnelheid van de romp en de tijdsduur tussen de piekhoeksnelheden van het bekken en de romp. Een uitstekende voorspelling was alleen mogelijk met een hiërarchisch lineair model, dat een individueel niveau toevoegt aan het groepsniveau. Zo is het mogelijk om de individuele elleboogbelasting op het veld te kwantificeren, op voorwaarde dat de voorspelling een mix is van groeps- en individuele niveaus.

Dit proefschrift wordt afgerond met een algemene discussie (Hoofdstuk 9), waarin we reflecteren op het proces dat we hebben doorlopen voor het bereiken van onze algemene doelen, methodologische overwegingen, de praktische toepassingen en toekomstige richtingen voor het onderzoeksveld. Bij het zoeken naar antwoorden op het ontstaan van UCL- en elleboogblessures kan worden geconcludeerd dat we ons specifiek moeten richten op de samenwerking en mechanische interactie tussen de structurele en dynamische stabilisatoren van de elleboog. Daarnaast moeten we rekening houden met de grote en de variabiliteit van de elleboogbelasting in relatie tot herhaaldelijk werpen binnen het individu. Voor blessurepreventie is het essentieel om de individuele belasting van de elleboog/UCL (intensiteit) te kwantificeren naast het aantal worpen (frequentie). Om in de toekomst blessures bij werpers te verminderen, is het belangrijk om de frequentie en intensiteit van elleboogbelasting op het veld te monitoren. Dit is mogelijk door de elleboogbelasting te voorspellen, aan de hand van draagbare sensoren die de kinematica van de bekken en romp meten tijdens elke training en wedstrijd. Longitudinale gegevens zullen nieuwe individuele informatie verschaffen over veranderingen in elleboogbelasting (grote en variabiliteit) en herstel, die mogelijk verband houden met overbelastingsblessures. Bovendien zijn bekken- en rompkinematica en intersegmentale timing belangrijk in relatie tot prestaties. Het gebruik van deze draagbare sensoren op de bekken en romp kunnen worden gebruikt om een "vroegtijdig waarschuwingssysteem" te ontwikkelen om atleten preventief te behoeden voor overbelastingsblessures en tegelijkertijd realtime feedback te geven om werpprestaties te verbeteren.

Liever luisteren dan lezen?
Luister hier naar de podcast.

ACKNOWLEDGMENTS

Alleen ga je sneller, samen kom je verder. Na een olympische wetenschapscyclus is het zover! In dit proefschrift lees je het resultaat van vier jaar promoveren, wat mij betreft is het goud waard. Net als bij een professionele atleet, zit hier een heel team achter. Zonder al deze mensen had ik hier nu niet gestaan en had je dit proefschrift niet kunnen lezen. Daarom wil ik iedereen bedanken die heeft geholpen.

Promotieteam

DirkJan, door mijn hoofd gaat de quote: "Keep it simple", maar voor dit dankwoord gaat dat niet op. Jij maakte mij enthousiast voor het (honkbal)onderzoek tijdens mijn bachelor. Tijdens mijn afstudeerfeest gaf je aan dat het over vier jaar weer zo'n feestje moest komen. Je liet me vrij in het begeleiden van studenten en in het bedenken van onderzoeksvragen. Je hebt een helikopter view en weet altijd meteen de essentie uit de discussie te halen. Hierdoor verloor ik me niet in alle mogelijkheden en ideeën, voor mij de perfecte begeleider.

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Marco, jouw naam wordt bij bewegingswetenschappen vaak in één zin gezegd met statistiek. Maar als ik Marco zeg dan zeg ik persoonlijk betrokken en communiceren op interactie en gevoel. Je neemt altijd de tijd voor mensen en vraagt ook echt door. Ik denk dat dit een unieke eigenschap is in de wetenschap, waar menig wetenschapper van kan leren. Ik ben heel blij dat jij mij zo op persoonlijke vlak hebt begeleid. Naast de persoonlijke gesprekken was er altijd ruimte voor luchtige gesprekken over petjes of F1 Tyrell auto's, jij weet overal wel iets van. Naast de interessante inhoudelijke discussie zorgde jouw geordendheid en oog voor detail voor structuur en netheid in mijn werk.

Promotiecommissie

Promotion committee (prof. dr. Babette Pluim, dr. Arnel Aguinaldo, prof. dr. Bart Koopman, and prof. dr. Geurt Jongbloed) I would like to thank you for reading my dissertation and for attending my PhD-defense.

Paranimfen

Ton, de eerste keer dat we elkaar ontmoette was er meteen een klik. Een koffietje drinken werd namelijk meteen een biertje in de zon op de VU. Er volgden vele koffietjes, of het nu bij jou of mij thuis was, op de universiteit, of op de sportvelden. We gingen als jut en jul op pad. We voelden elkaar goed aan en hebben de perfecte sweetspot om te schakelen tussen serieus en lekker gek doen. Ik heb veel geleerd van je structuur, programmeer skills en doorzettingsvermogen.

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Technische Universiteit Delft

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VU Amsterdam
Bewegingswetenschappen
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Alumni (Voormalige studenten in het project)
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Vrienden en familie

Vrienden

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Familie

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PhD PORTFOLIO

Courses and workshops	
PhD start-up module A,B&C (2 ECTS)	2018
OpenSim Workshop (3 ECTS)	2018
Leadership, teamwork and group dynamics(2 ECTS)	2019
Using Python for research (5 ECTS)	2020
Cross cultural differences(1 ECTS)	2020
Managing the academic publication review process (1 ECTS)	2020
Using creativity to maximize productivity and innovation in your PhD (2 ECTS)	2020
Analysis of interviews and other unstructured data (2 ECTS)	2022
Implementation network (5 ECTS)	2021
3mE video competition (1 ECTS)	2021
English for academic purposes EAP3 (3 ECTS)	2021
Effective negotiation (1 ECTS)	2021
Managing myself and leading others (1.5 ECTS)	2021
Writing a dissertation PROM3 (3 ECTS)	2022
Marketing tools to position yourself on the job market (0.5 ECTS)	2023

(Inter)national conferences	
International Sports Engineering Association Conference (ISEA), *virtual*	2020
Dutch Conference for Biomedical Engineering (BME), *virtual*	2021
International Society of Biomechanics (ISB),*virtual*	2021
North American Conference of Biomechanics (NACOB), *Ottowa*, *Canada*	2022
Tecknowlodgy, Maarsen, *Nederland*	2022
Dag van het sportonderzoek, *Zwolle*, *Nederland*	2022
International Society of Biomechanics (ISB), *Fukuoka*, *Japan*	2023
International Society of Sport Biomechanics (ISBS) mid-year symposium, *virtual*	2023

Conference and symposium presentations	
The role of variability and fatigue quantified *European Elbow and Shoulder Conference (oral)*	2019
Are UCL injuries a matter of bad luck? The role of variability and fatigue quantified, *ISEA conference (oral)*.	2020
Establishing the role of elbow muscles in fastball pitching *BME conference (oral)*	2021

Quantifying the within individual elbow load variability in youth elite baseball pitchers, *International Society of Biomechanics (oral)* 2021
Individual elbow and shoulder load variability in youth elite baseball pitchers, *International Shoulder Group conference (oral)* 2022
Magnitude and variability of elbow load in repetitive baseball pitching. *North American Conference of Biomechanics (poster)* 2022
Technologisch maatwerk als interventie voor sportblessurepreventie *Dag van het sport onderzoek (oral)* 2022
Energy flow in the lower extremities *International Society of Sport Biomechanics mid-year symposium (oral)* 2023
Potential injury mechanisms in ulnar collateral ligament injuries *International Society of Biomechanics (poster)* 2023

Teaching

Lecture: 'Voorwaartse en inverse dynamische modellen' 2018-2022
Bachelor Klinische technologie, TU Delft
Anatomy and control, lecturer and assignments 2018-2022
Minor Biomechanical engineering, TU Delft
Lecture: 'Rigid body dynamics' 2018-2022
Master Biomechanical Engineering, TU Delft
Guest lecture: 'Breaking the High Load' 2019-2021
Bewegingstechnologie, de Haagse Hogeschool
Guest lecture: 'De slimme sporter' 2020
Primery school Michaëlschool, Rotterdam
Guest lecture: 'Doing a PhD in biomechanics' 2022
Research master Human movement sciences, Vrije Universiteit
Guest lecture: 'Biomechanica in de (Top)sport' 2023
Highschool O.R.S. Lek en Linge, Culemborg

Supervising

Master students

Eva Galjee. Establishing the capacity of the muscles around the elbow joint to compensate for the external valgus moment during a fastball pitch: An electromyographic study. 2018
Master, Biomechanical Engineering, TU Delft
Patrick Sengalrayan. Upper extremity injury prediction in elite youth baseball pitchers using classification methods. 2018
Master, Biomechanical Engineering, TU Delft

A

Xinyu Liu. Tennis Stroke Recognition: Stroke classification using inertial measuring unit and machine learning algorithm in Tennis. 2019
Master, Biomechanical Engineering, TU Delft

Foskien Bouman. Establishing the elbow load and the within-pitcher load variability during a baseball pitch in relation to the ball speed. 2020
Master, Biomechanical Engineering, TU Delft

Anne de Swart. The role of the lower extremities in the energy flow during a baseball pitch. 2020
Research master, Human movement sciences, VU Amsterdam

Maxime Schouten. Effect of training on the ulnar collateral ligament and ulnohumeral joint gap in elite youth baseball pitchers. 2020
Master Musculoskeletal Physiotherapy Sciences, VU Amsterdam

Celine Bouwmeester. Pitch type classification based on pelvis and trunk IMU data. *Master, Biomechanical Engineering, TU Delft* 2020

Erik Faneker. The kinetic chain and serve performance in elite tennis players. 2021
Master, Human Movement Sciences, VU Amsteram

Jeffrey van Goethem. The effect of hand grip force, elbow valgus stress and repetitive pitching on the humeroulnar joint gap and the ulnar collateral ligament in baseball pitchers. 2021
Master Musculoskeletal Physiotherapy Sciences, VU Amsterdam

Lotte van der Pijl. Identification of muscles (un)loading the UCL during baseball pitching. *Master, Biomechanical Engineering, TU Delft* 2021

Chrysanthi Zoumpliou. Imaging assessment of ulnar collateral ligament (UCL) injury through ligamentous thickness and gapping of the ulnohumeral joint space (UHJS) in symptomatic & asymptomatic professional baseball pitchers: a meta-analysis. 2021
Master Musculoskeletal Physiotherapy Sciences, VU Amsterdam

Thomas van Hogerwou. Confirmatory Factor Analysis as a Biomechanical Tool: A Novel Approach to Investigating Different Fatigue Aspects in Baseball Pitching. *Master, Biomechanical Engineering, TU Delft* 2022

Bachelor students

Dieuwertje den Besten, Stevie Niks, Maaike Westerman. Preventie van UCL-schade bij Pitchers door Sleeve. 2019
Bachelor, werktuigbouwkunde, TU Delft

Bastien Giraud, Arjen Peijen, Friso Topper, Thomas Boer, Bart Horstman. Measurement shirt for the baseball pitch. 2019
Bachelor, werktuigbouwkunde, TU Delft

Moescha van Leeuwen. Risico factoren voor mediale elleboog blessures in het tennis. 2020
Bachelor, Human Movement Sciences, VU Amsterdam

Alban Broze, Laurens Nievelstein, Moniek van Zon, Isa Huipen. Identifying Muscle Fatigue in the Biceps Brachii using a Mechanomyography Sensor. 2020
Bachelor, werktuigbouwkunde, TU Delft

Natasja Boon. De mogelijke verschuiving van tennisblessures over de tijd tussen regio's binnen de bovenste extremiteit. 2021
Bachelor, Human Movement Sciences, VU Amsterdam

Noah Baltus. Onderzoek op het effect van carbonschoenen op spierintensiteit en grondcontacttijd. 2022
Bachelor, werktuigbouwkunde, TU Delft

Jordi Vlak, Joris Meursing, Ko Dirkzwager, Martijn Mensonides. Inside the tennis swing. 2022
Bachelor, werktuigbouwkunde, TU Delft

Outreach

Wetenschappelijk pitchen en serveren, *stadskrant tecktalk Delft*	2019
Pijnloos pitchen, *de ingenieur*	2019
Prevention vs performance, *video TU Delft TV*	2019
Onderzoek naar blessures en prestaties bij honkbalpitchers, *Fastball magazine*	2020
Blessures voorkomen met een sensor shirt, *video NWO Tecknowledgy*	2021
Wimbledon, Sportlab Sedoc *Dutch national television*	2022
Podcast 'breaking the high load'	2022
Website www.bartvantrigt.nl	2023

Popular Science Presentations

Famelab competition www.famelab.nl	2019
Guest speaker and host at the Karel Luyben lezing in Delft	2019
Science meets Arts presentation at Maas Theater Rotterdam	2022

Grants

Implementatie netwerk sport en bewegen (€80.000)	2021

Awards

Gerrit-Jan van Ingen Schenau promising young scientist-award, 2017
FGB VU Amsterdam

Gewaardeerd! award, *KNAW* 2021

LIST OF PUBLICATIONS

Publications as part of this thesis

Van Trigt, B., Vliegen, L., Leenen, T., & Veeger, D. (2021). The ulnar collateral ligament loading paradox between in-vitro and in-vivo studies on baseball pitching (narrative review). *International Biomechanics*, *8*(1), 19-29.

van Trigt, B., Galjee, E., Hoozemans, M. J., van der Helm, F. C., & Veeger, D. H. (2021). Establishing the role of elbow muscles by evaluating muscle activation and co-contraction levels at maximal external rotation in fastball pitching. *Frontiers in sports and active living*, *3*, 698592.

Van Trigt, B., Leenen, T., Hoozemans, M., Helm, F. F. V. D., & Veeger, D. (2020). Are UCL Injuries a Matter of Bad Luck? The Role of Variability and Fatigue Quantified. In *Proceedings*(Vol. 49, No. 1, p. 107). MDPI.

Van Trigt, B., Bouman, F. F., Leenen, A. J., Hoozemans, M. J., Van der Helm, F. C., & Veeger, D. (2022). Quantifying Within-Individual Elbow Load Variability in Youth Elite Baseball Pitchers and Its Role in Overuse Injuries. *Applied Sciences*, *12*(13), 6549.

van Trigt, B., van Hogerwou, T., Leenen, T. A., Hoozemans, M. J., van der Helm, F. C., & Veeger, D. H. (2023). Magnitude and variability of individual elbow load in repetitive baseball pitching. *Scientific Reports*, *13*(1), 1-10.

Gomaz, L.*,**van Trigt, B*.,** Veeger, D., & van der Meulen, F. (2023). Predicting elbow load based on individual pelvis and trunk (inter)segmental rotation in fastball pitching. *Sports Biomechanics (revisions)* *Shared first authorship

Other publications

Ciszewski, M., Söhl, J., Leenen, T., **van Trigt, B**., & Jongbloed, G. (2023). Credibility of high $ R^ 2$ in regression problems: a permutation approach. *arXiv preprint arXiv:2305.02685*.

van Trigt, B., Hoozemans, M. J., Eygendaal, D., & Veeger, H. E. J. (2022). Biomechanics in overhead sports. In *Elbow work is teamwork.: The treatment of basic elbow pathology*. Arko Publishers.

Leenen, A. J. R., **van Trigt, B**., Hoozemans, M. J. M., & Veeger, H. E. J. (2022). Fastball pitching performance only slightly decreases after mobility impediment of the pelvis and trunk—Do (catch-up) compensation strategies come into play?. *Frontiers in Sports and Active Living*, *4*, 1044616.

de Swart, A. F., **van Trigt, B**., Wasserberger, K., Hoozemans, M. J., Veeger, D. H., & Oliver, G. D. (2022). Energy flow through the lower extremities in high school baseball pitching. *Sports Biomechanics*, 1-15.

Gomaz, L., Veeger, D., van der Graaff, E., **van Trigt, B.,** & van der Meulen, F. (2021). Individualised ball speed prediction in baseball pitching based on IMU data. *Sensors*, *21*(22), 7442.

Zhan, S., Jiang, D., Ling, M., Ding, J., Yang, K., Duan, L., **van Trigt, B.,** ... & Hu, H. (2021). Fixation effects of different types of cannulated screws on vertical femoral neck fracture: A finite element analysis and experimental study. *Medical Engineering & Physics*, *97*, 32-39.

Veeger, T. T**., van Trigt, B**., Hu, H., Bruijn, S. M., & van Dieën, J. H. (2020). Fear of movement is not associated with trunk movement variability during gait in patients with low back pain. *The Spine Journal*, *20*(12), 1986-1994.

Leenen, T., **van Trigt, B.,** Hoozemans, M., & Veeger, D. (2020, June). Effects of a disturbed kinetic chain in the fastball pitch on elbow kinetics and ball speed. In *Proceedings* (Vol. 49, No. 1). MDPI.

Van Trigt, B., Schallig, W., Van der Graaff, E., Hoozemans, M. J., & Veeger, D. (2018). Knee angle and stride length in association with ball speed in youth baseball pitchers. *Sports*, *6*(2), 51.

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ABOUT THE AUTHOR

Bart van Trigt was born on the 7th of June, 1993, in the city of Goes. As a young child, he was expected to go to sleep. However, instead of sleeping, he immersed himself in the pages of an anatomy book and a sports catalog. At the Ostrea Lyceum High School, he discovered his passion for physics, biology, and mathematics. His enthusiasm for these subjects and his love for sports motivated him to study Human Movement Sciences at the VU Amsterdam.

In 2015, Bart started with the research master, delving deeper into biomechanics. He went to China to improve his research skills at the Shanghai Sixth People's Hospital. There, he gained valuable insights into different cultures and discovered more about himself. Throughout his research master's, he actively engaged as a board member of the Faculty of Human Movement and Behavioural Sciences. He also earned a teaching certification for higher education. In 2017, he obtained his master's degree and started as a lecturer in biomechanics, statistics, and physiology at The Hague University of Applied Sciences.

While guiding students, Bart realized his passion for research and aspired to pursue a PhD. He set specific criteria for his doctoral research: it had to revolve around sports, biomechanics, societal relevance, and collaborative efforts. In 2018, he found the perfect match in the "Breaking the High Load" research project, which eventually led to this dissertation.

Even after three decades, Bart continues his nocturnal reading habits, constantly exploring new insights for (technological) innovation, which he applies to his research. Beyond his scholarly pursuits, he is dedicated to implementing his knowledge to assist others in enhancing their performance and ensuring they stay healthy. In 2021, he started working as an implementation specialist in the 'Sport en Bewegen' network. As a future pracademic, he aims to build the bridge between academia and practice.

Hoe was de samenwerking met mij?
Een student, collega en begeleider vertellen.

Keep the pitcher's elbow load in the game

Biomechanical analysis of injury mechanisms in baseball pitching towards injury prevention