Establishing the capacity of the muscles around the elbow joint to compensate for the external valgus moment during a fastball pitch

An electromyographic study

E.N. Galjee

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by

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Preface

This thesis concludes the research project executed to complete the MSc programme Biomedical Engineering at DELFT UNIVERSITY OF TECHNOLOGY (TU Delft). The project was executed under the supervision of the TU Delft as part of the overarching Citius Altius Sanius project, a project focusing on specific sports and injuries. The current research focussed on a topic of which little was known in the literature currently available. When applying to this research position, I was well aware of the challenges ahead. I had to be open minded with respect to the research methods used, combined with a hands on and practical mentality. This brought me to a process with unexpected challenges in the measurement setup. The time spent on finding out the right measurement setup has been a great learning experience. To find out that the final portable measurement setup I developed actually works to acquire detailed muscle activity data has been exciting.

I would like to thank René van der Horst and Ayla Engels for hosting the training hall of the baseball club Bluebirds for the measurements, and for exciting some pitchers to participate in this study. Naturally, I want to thank all the pitchers for their participation and patience.

In particular I would like to thank Bart van Trigt for your daily guidance and advise, but also for stimulating me to work independently and to choose my own path during the research project. We have discussed many subjects, varying in complexity and relevance, for which I acknowledge your patience. I want to thank you for the pleasant atmosphere during our personal and team meetings. Additionally, I want to thank DirkJan Veeger for being the chair of the committee. Not only your overall governance but especially your critical in depth comments during the meetings has been very helpful.

Lastly, I would like to thank Raoul who has been my biggest supporter, encouraging me to do the best I could.

E.N. Galjee
Delft, May 2020

Abbreviations

Abbreviation	Meaning
BR	Ball Release
EMG	Electromyography
ESM	Extensor supinator mass
EVM	External valgus moment
FC	Foot contact
FPM	Flexor pronator mass
fps	Frames per second
MA	m. anconeus
MBB	m. biceps brachii
MER	Maximum External Rotation
MPT	m. pronator teres
MTLH	m. triceps lateral head
MVC	Maximum Voluntary Contraction
sr	Sample rate
UCL	Ulnar Collateral Ligament

Table 1: Abbreviations list

Contents

Abstract

Baseball pitching is a movement wherein an external valgus moment around the elbow joint regularly causes an ulnar collateral ligament (UCL) injury. A proven relationship between the muscle activation around the elbow joint and its capacity to compensate for the external valgus moment during a baseball pitch allows predicting the likelihood of a UCL injury within pitchers in the future.

The present study establishes the generic muscle activity around the elbow joint during a fastball baseball pitch to investigate the capacity of the muscles to compensate for the external valgus moment actively and thereby prevent a UCL injury.

Six uninjured, experienced recreational adult pitchers, participated in this study (age: 25 ± 2 years; body height: 188 ± 10 cm; body mass: 77 ± 15 kg). 2000 Hz surface ElectroMyoGraphy (sEMG) was used to measure the muscle activity around the elbow joint in 15 fastball pitches for each participant. Before the pitch measurement, participants had to perform maximum voluntary contractions (MVC).

The signals were corrected to an electromechanical delay of 50 ms and normalized to either MVC, or to the maximum of the signal itself. After that, the mean values were calculated for the instance of foot contact, maximum external rotation and ball release separately over the participants. A repeated measures ANOVA was performed to observe whether the mean activity is significantly higher at maximum external rotation compared to the moment of foot contact and ball release to compensate for the peak external valgus moment.

Significant peak activity was found at maximum external rotation for all muscles, compared to the instance of ball release. The parallel activity of the flexor pronator mass and m. pronator teres at maximum external rotation enhances a compensating effect to the external valgus moment by its directly counteracting tension. Furthermore, the results support a co-contraction between the flexor pronator mass:extensor supinator mass and m. triceps lateral head: m. biceps brachii muscle pairs to compensate for the external valgus moment by a compression force to the elbow joint. The generic function of the m. anconeus in the fastball baseball pitch is still debated due to the inconsistent results over the different pitchers in this study.

This study provides evidence that the muscles around the elbow joint can compensate for the external valgus moment during a fastball pitch. These results provide possibilities for using sEMG to assess the muscle activation pattern of individual pitchers as support to predict and prevent UCL injuries in pitchers in the future.

1 Introduction

Based on Major League Baseball injury data, injuries to the throwing elbow account for approximately 16% of all injuries in baseball players, 25% of all injuries in pitchers and 22% of the total disabled days [7]. The elbow disability represents more than twice the second most costly injury, being hamstring strains [16]. These high injury rates point out that reducing of such injury is desired. It is better to prevent than to cure, to both save costs and protect the pitcher from suffering.

Previous studies have indicated that as the arm transitions through the arm cocking phase and acceleration phase of throwing, the point when the arm reaches maximum external rotation (MER), the elbow experiences the highest external valgus moment [3, 6, 12–14, 17, 26, 28, 33, 34] (see figure 1.1). The period prior MER is known as the arm cocking phase, starting when the leading foot contacts the mount. When the arm reaches MER, the cocking phase transitions into the arm acceleration phase, which last till the moment of ball release (see figure 1.4). The moment from foot contact till ball release takes only about 170ms [3, 6, 12, 13, 26, 28, 33]. Throwing a baseball at such high speeds places greater stress on the ulnar collateral ligament (UCL) than it can withstand [11], leading to tear. The valgus moment attempts to rotate the forearm to the lateral side concerning the upper arm and consequently involves a tensile force to the medial elbow joint structures (see figure 1.3). The UCL is seen as the primary restraint against an external valgus moment, positioned on the medial aspect of the elbow joint between the distal humerus and the proximal ulna [2, 4, 23, 24, 29]. Therefore, the instability resulting from UCL tear is a significant impairment for a baseball pitcher.

Elbow joint stability is determined by structural components such as joint articulations and ligaments, and functional components such as muscle forces [27, 29, 30]. Different in-vitro studies use stress-test setups to quantify the valgus stabilizing function of the passive muscle tension in the forearm, with the skin and subcutaneous tissue removed. The flexor pronator mass (FPM) is stated as a significant contributor to the valgus stability [9, 22, 27, 30, 32] by its direct effect of the counteracting tension. The FPM refers to the collection of muscles (m. flexor digitorum superficialis, m. flexor carpi radialis, m. flexor carpi ulnaris and m. pronator teres) that collectively cross the elbow, forearm, wrist and finger joints at the anterior side of the forearm, used for wrist, finger and elbow flexion as well as pronation. Two studies show that a tension of the extensor supinator mass (ESM) induce a valgus motion in an elbow angle ranging from 30 to 90 degrees [22, 30]. The ESM refers to the collection of muscles (m. supinator, m. brachioradialis, m. extensor carpi radialis longus and brevis, m. extensor digitorum communis, and m. extensor carpi ulnaris) on the posterior side of the forearm used for wrist, finger, and forearm extension as well as supination. Simulated loading of the m. biceps brachii and m. triceps brachii significantly decreased varus-valgus elbow laxity in several in-vitro studies [24, 27, 30]. An indirect effect to resist to the valgus moment is achieved by the m. biceps brachii and m. triceps brachii tension which create an increasing joint contact force and as such resistance against joint wedging [24, 27, 30]. However, these in-vitro research conditions are not reflective for the capacity of the muscles around the elbow joint to compensate for the faced external valgus moment in the baseball pitching. It is fundamental to know whether the muscle tension is passive or active around the elbow joint, to clarify the muscles' capacity to compensate for the external valgus moment. Therefore, the presence of muscle activity should be identified and quantified during pitching.

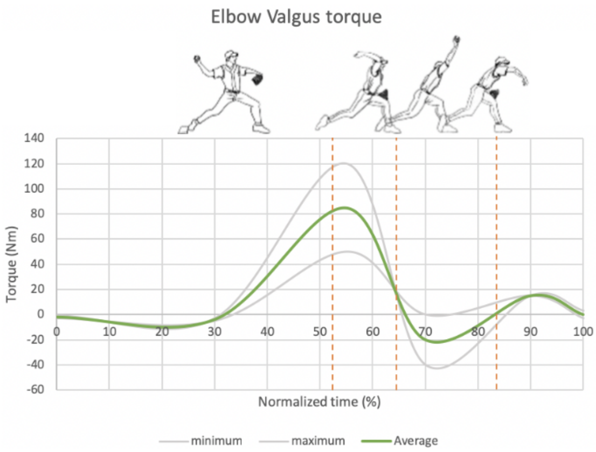


Figure 1.1: The external valgus moment around the elbow joint. A positive value means a valgus moment and a negative value means a varus moment. The vertical dashed line lines represents maximum external rotation, ball release and maximum internal rotation respectively. The thick line represents the mean achieved from the data of several studies [3, 6, 13, 14, 17, 28, 33, 34]. The thin grey lines represents the minimum and maximum values from these researches.

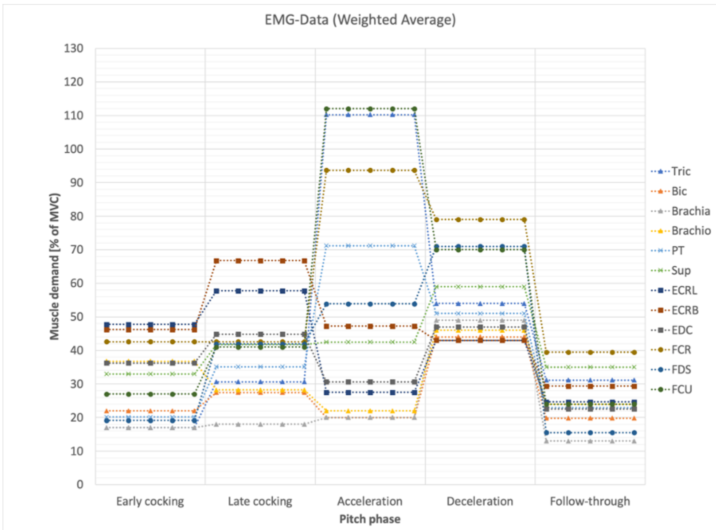


Figure 1.2: Weighted average over all EMG data achieved from uninjured (ex)professional/collegiate pitchers in literature [10, 15, 20, 31] (figure created by author)

Four studies on EMG activity of the forearm muscles in the throwing arm are documented in literature (see figure 1.2). However, all studies averaged the EMG activity over each pitch phase and the method is marginally documented, resulting in limited information on the activation pattern of the muscles around the critical time instance of maximum external rotation of the throwing arm. These studies show a significant activity (> 50 % of maximum voluntary contraction) in either the cocking and acceleration phase [10, 15, 20, 31]. The upper arm muscles are included in three EMG studies [10, 15, 20], in which the m. triceps brachii shows very high activity (> 90 %) in the acceleration phase and high activity (40 % - 60 %) in the cocking phase. The m. biceps brachii shows in both phases moderate activity (20 % - 40 %). These documented activation patterns suggests that the muscles in the throwing arm might be capable to compensate for the external valgus moment at the critical instance of the pitch motion. More detailed EMG data are essential to ensure a reliable assessment of the capacity of the muscles to actively counteract the external valgus moment during a baseball pitch.

A proven relationship between the muscle activation around the elbow joint and its capacity to compensate for the external valgus moment during a baseball pitch allows predicting the likelihood of a UCL injury within pitchers. These insights can be used by physicians and coaches to support adaptations in the pitching technique to prevent UCL injuries in the future. Therefore, this research aims to determine whether the muscles around the elbow joint show a significant activity around the moment of maximum external rotation during a fastball pitch. It is hypothesized that: (1) For a direct effect - significant muscle activation would be expected around the instance of MER for the FPM and pronator teres to counteract for the external valgus moment, and higher when compared to the instance of FC and BR. (2) For an indirect effect - significant co-contraction activity would be expected by the FPM:ESM muscle pair and m. biceps brachii:m. triceps lateral head muscle pair at the instance of MER to compensate for the external valgus moment, and higher when compared to the time of FC and BR.

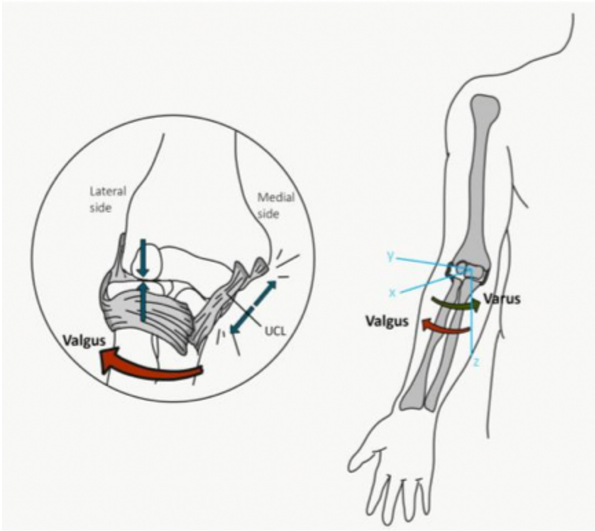


Figure 1.3: Visualization of the external valgus moment around the right elbow joint (anterior view). Elbow joint motion is described in the ZXY Euler sequence, where the first rotation is around the z–axis of the humerus, the second around the floating x–axis perpendicular to z and y and the third rotation around the yaxis of the ulna. Valgus and varus movements are rotations around the x–axis (figure created by author).

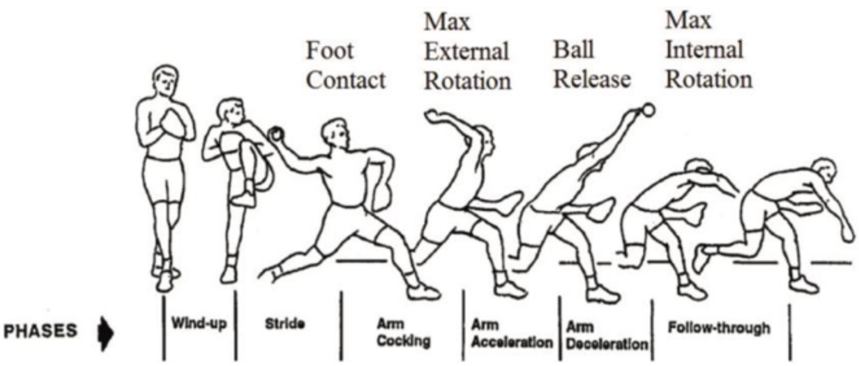


Figure 1.4: The pitch cycle and its events [13]

2 Methodology

2.1. Participants

Six uninjured, experienced recreational adult pitchers, participated in this study (age: 25 ± 2 years; body height: 188 ± 10 cm; body mass: 77 ± 15 kg). Four were right-handed, and two left-hand dominant. They all started playing baseball at an age of 8 ±2 years and pitching at 10 ± 3 years old. All participants did not experience any physical complaints in the past six month at the moment of the measurement. The Ethics Committee of the Technical University Delft approved the research project and the participants signed an informed consent after being informed on the procedure and aims of the study.

2.2. Experimental procedure

The measurements were performed at indoor facilities. To identify a potential muscle activity pattern, participants had to perform fifteen consecutive fastball pitches (see figure 2.1). Prior to the pitch measurement, participants had to perform maximum voluntary contractions (MVC) in accordance to the functional characteristics of the muscles (see table A.1 in chapter A.1.1 of the Appendix), of which surface ElectroMyoGraphy (EMG) activity was recorded and used for normalization purposes. The participant had to gradually build up muscle force to maximum exertion in 3 s, hold it for 3 seconds and gradually relax in again 3 s. Each specific MVC was repeated three times. After this, the participant were given an unlimited time to do their own warming-up before the pitch measurements started. A pitch mount was installed from which the participant had to perform their pitches to a marked strike zone in the net (imaginary catcher), which was set at a formal baseball field distance to the home plate (see figure 2.1a and 2.1c). The participants were instructed to wear their own preferred clothes and baseball glove, but without a shirt during the pitch measurement to avoid interference of the EMG signal. Three researchers were involved during the pitch measurement. The first researcher was responsible to start the video recording. Thereafter, the second researcher had to start the speed gun from behind the net in the direction of the participant while the third researcher had to push a LED button attached to the participant. Researcher three stepped aside after pushing the LED button and instructed the participant to pitch (see figure 2.1c for the position of each researcher and the participant). The process of starting the video recording, starting the speed gun, switching on the LED was repeated for each pitch separately.

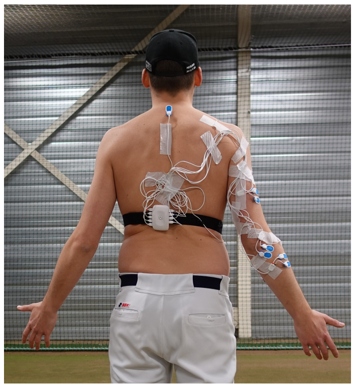
2.3. Data acquisition

The activity of six skeletal muscles of the throwing arm during a fastball pitch (see figure 2.1b) was recorded using surface ElectroMyoGraphy (EMG). Data were collected using Physioplux (Plux, Arruda dos Vinhos, Portugal). Except for the m. pronator teres, the wrist-hand flexor and extensor muscle groups in the lower arm were measured as bundles, being the flexor-pronator mass (FPM) and the extensor-supinator mass (ESM) respectively. In addition, the the activity of lateral head of triceps, anconeus and biceps (combined recording of both heads) were measured. The reference electrode was placed at the 7th cervical vertebrae.

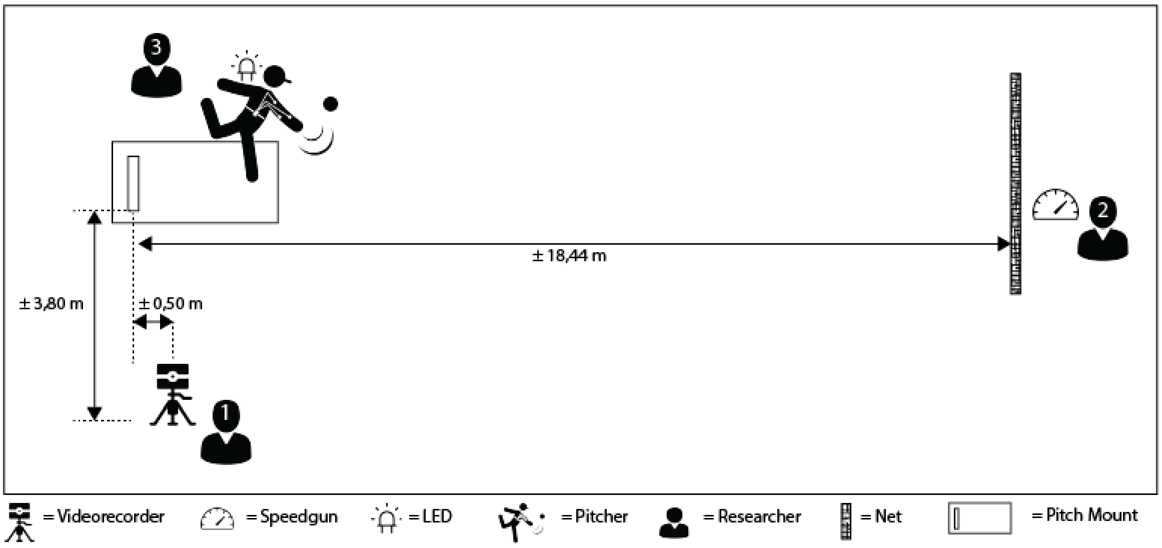
After preparation, bipolar, disposable, pre-gelled Ag/AgCl surface electrodes were placed on the pitchers' skin with an inter-electrode distance of 20 mm. The exact placement of the electrodes was based on [1] (see table A.2 and figure A.1.2 in chapter A.1.2). The skin was shaved and cleaned with alcohol before the electrode attachment and the electrode cables were fixed to the skin to avoid cable movement artefacts in the signal and to minimize the risk of loosening the electrodes from the skin during the pitch movement. When an electrode was released during a pitch, this was noted to exclude from the data analysis, and the electrode was attached again. The raw data output signals were analog filtered at 25-500 Hz by the hardware of the EMG sensors, with a sensor gain (G_{EMG}) of 506 and an operating voltage (VCC) of 3V. The EMG data were acquired at a sampling frequency of 2000 Hz and 16-bits (n).

All fifteen consecutive fastball pitches were recorded in one EMG dataset. The kinematic data were collected with a high-speed camera (Sony RX100V) at a frame rate of 240 fps. The video recorder was set in a side view position relative to the pitch mount (camera height: 1.25m, distance to mount: ±3.80m), with the participant's body entirely visible trough out the pitch cycle (see figure 2.1c). A LED light was connected to the same hub as the EMG sensors. The ball speed of each pitch was recorded in the direction of the gun, with the Stalker pro radar gun (Stalker Radar, Plano, TX, USA).

(a) Photo of the experimental setup.



(b) Photo of the participant with electromyography sensors attached.



(c) Visualisation of the experimental setup.

Figure 2.1: The experimental setup showing the participants position at the pitch mount to perform the fastball pitches, the electrodes for EMG recording and a visualisation of the experimental setup.

2.4. Data analysis

Adobe Premier Pro 2020 was used for single-frame viewing of the separate pitch video recordings. The video sample at the instance of foot contact (FC), maximum external rotation (MER) and ball release (BR) were determined for each pitch from the video recording. FC is the moment when the entire leading foot contacts the mount. The throwing arm reaches MER at the point that the shoulder transitions from an external rotation to an internal rotation [11, 13, 33]. The moment when the pitcher releases the ball is the instance of BR (see figure 2.2). The flashlight of the LED in the video recording was used to synchronize the pitch motion to the EMG signals. The timing of the determined pitch event samples from the video recording were subsequently linked to the recorded EMG signals based on the relative sample frequencies.

The EMG signals were extracted by the use of the python programming language (version 3.7, Python Software Foundation, https://www.python.org/). In support of the data analysis description, the procedure from loading the raw data in python till the extraction of the resulting graphs is illustrated in a flow in Figure A.2 in appendix A.1.3. The flashlight of the LED caused a block signal which was used to cut the total EMG dataset into signals per pitch. The EMG signal of each muscle within the fifteen consecutive pitches was synchronized to the time of FC and cut at 300 (0.15s) samples prior and 600 samples post FC (0.3s), resulting in a fifteen pitch signals of 450ms for each muscle per pitcher. The signals of the noted loosened electrode were excluded from the analysis. For each participant separately, the raw EMG signals of the fastball pitches were first rectified, after which the mean signal time-series of each muscle was calculated. Thereafter, each mean signal time-series was normalized to the muscle specific determined MVC values, or the maximally obtained in-throw value, ensuring values were never higher than 100%. Primarily, the reference value was obtained as the mean of the three maximums of the MVC test. However, in some tests, the maximum of the 15 pitch mean signal showed higher muscle activity than this reference value. Therefore, in these cases, the maximum of the 15 pitch averaged signal was obtained as 100% muscle activity reference value to which the mean signal time-series where normalized. The same normalization approach was applied to the individual pitch signals. These normalized individual pitch signals were used to determine the standard deviation of each participant.

To correct for the time difference between activation onset and force buildup, an electromechanical delay (EMD) correction of 50 ms [3] was applied to the normalized mean signal time-series.

The 10ms mean value was calculated per mean muscle signal time-series, including the applied EMD, at the pitch events FC, MER and BR for each participant separately (5ms prior till 5ms post the concerned event).

The muscle activation ratios at FC, MER and BR were calculated to establish the presence of the hypothesized co-contraction of the FPM:ESM and m. triceps lateral head:m. biceps brachii muscle pairs. Muscle activation ratios were calculated at FC, MER and BR by dividing the pitch event specific 10ms mean values of the two concerning muscles for each participant separately.

The total mean for the 10ms mean values and muscle activation ratios was calculated over all participants for each pitch event (FC, MER and BR) separately. These total mean values were used for the analysis of the representation of the muscle activation pattern in fastball pitching to determine whether the muscles around the elbow joint reveals a significant activity around the moment of maximum external rotation to compensate for the external valgus moment in general and, in particular whether the activity is more at MER compared to the moment of FC and BR. To allow for generalized comparisons, different ranges of muscle activity are

(a) Foot Contact (b) Maximum External Rotation (c) Ball Release

Figure 2.2: Video samples of selected pitch events

prescribed in table 2.1.

The video analysis tool 'Tracker' (version 5.1.3) was used to determine the elbow flexion angle throughout the pitch within pitchers. The acquired flexion angles were used to analyze the muscle movement based on the mean signal time-series, including EMD. The muscle movement analysis was used to detect the occurrence of co-activations.

%-reference	Contraction Level
0 - 20	Low activity
21 - 40	Moderate activity
41 - 60	High activity
> 60	Very high activity

Table 2.1: Contraction Level Classification

2.5. Statistical analysis

The effects of the independent timing of FC, MER and BR on the mean muscle activity and ratios were analyzed by the use of a 3 (pitch events) x 6 (participants) x 15 (pitches) repeated measures ANOVA including a Greenhouse-Geisser correction. Pairwise comparisons were performed using a Bonferroni correction. This statistical design was chosen to quantify the results obtained regarding the interaction between the independent variables and provided insight into the hypotheses.

For all analysis, the significance level was set a priori to $p<0.05$. All data were analyzed using SPSS (version 25; IBM Corporation).

3

Results

3.1. Muscle activity at FC, MER and BR

The signals of the noted loosened electrode were excluded from the analysis. The m. triceps lateral head electrode was loosened during the ninth and tenth pitch of participant 4 and once during the third pitch of participant 5. The m. anconeus loosened once during the seventh pitch of participant 6 and the fifteenth pitch of participant 7. The m. biceps brachii loosened only once for participant 7, during the fourth pitch. resulting in three different muscle electrodes loosened (m. triceps lateral head, m. anconeus, m. biceps brachii) for 6 pitches in total over all participants. The group mean signal (and standard deviation) with corrected EMD across the 6 participants is presented in figure 3.1. Figure 3.2 shows the observed normalized mean signal time-series per muscle for each participant separately, corrected for EMD. These individual participants results are evaluated on group level. A typical example of a rectified raw EMG signal is presented in figure A.3 in appendix A.2.2.

Figure 3.3 presents the group mean (and standard deviation) across results of the 6 individual participants of the 10ms mean values at foot contact (FC), maximum external rotation (MER) and ball release (BR). The peak activity of each individual muscle was observed at MER (see figure 3.3). In particular, a high activity of the flexor pronator mass (FPM) (42 ± 21%) and m. triceps lateral head (MTLH) (45 ± 25%) was seen at MER, while the other muscles revealed a moderate activity (ranging between 24% and 38%). At the instance of FC was a moderate activity observed for the FPM, m. pronator teres (MPT), m. anconeus (MA) and m. triceps lateral head (MTLH) (ranging between 21% and 36%), while the ESM and m. biceps brachii revealed a low activity. All muscles decreased to a low activity at BR (<19%).

The repeated measures ANOVA determined that the mean activity of each individual muscle was significantly different between pitch events ($p<0.01$). The post hoc tests revealed a significant higher muscle activity for the m. biceps brachii (MBB)($p<0.01$) at MER compared to FC. The post hoc test revealed a significant effect of higher muscle activity at MER compared to the magnitude at BR for all muscles ($p<0.01$).

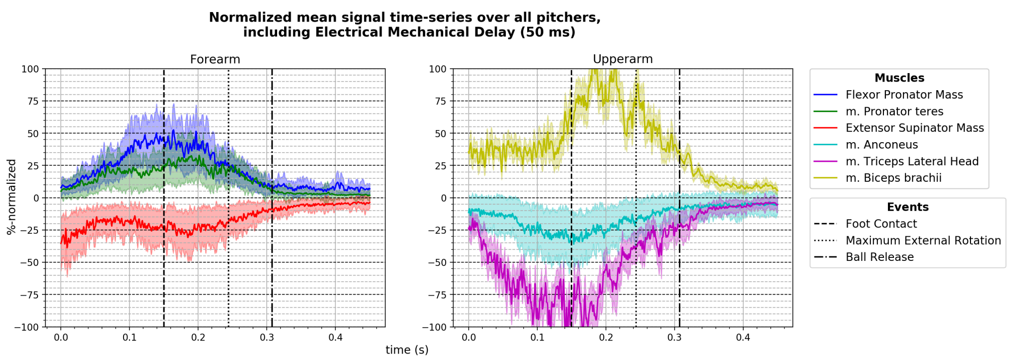
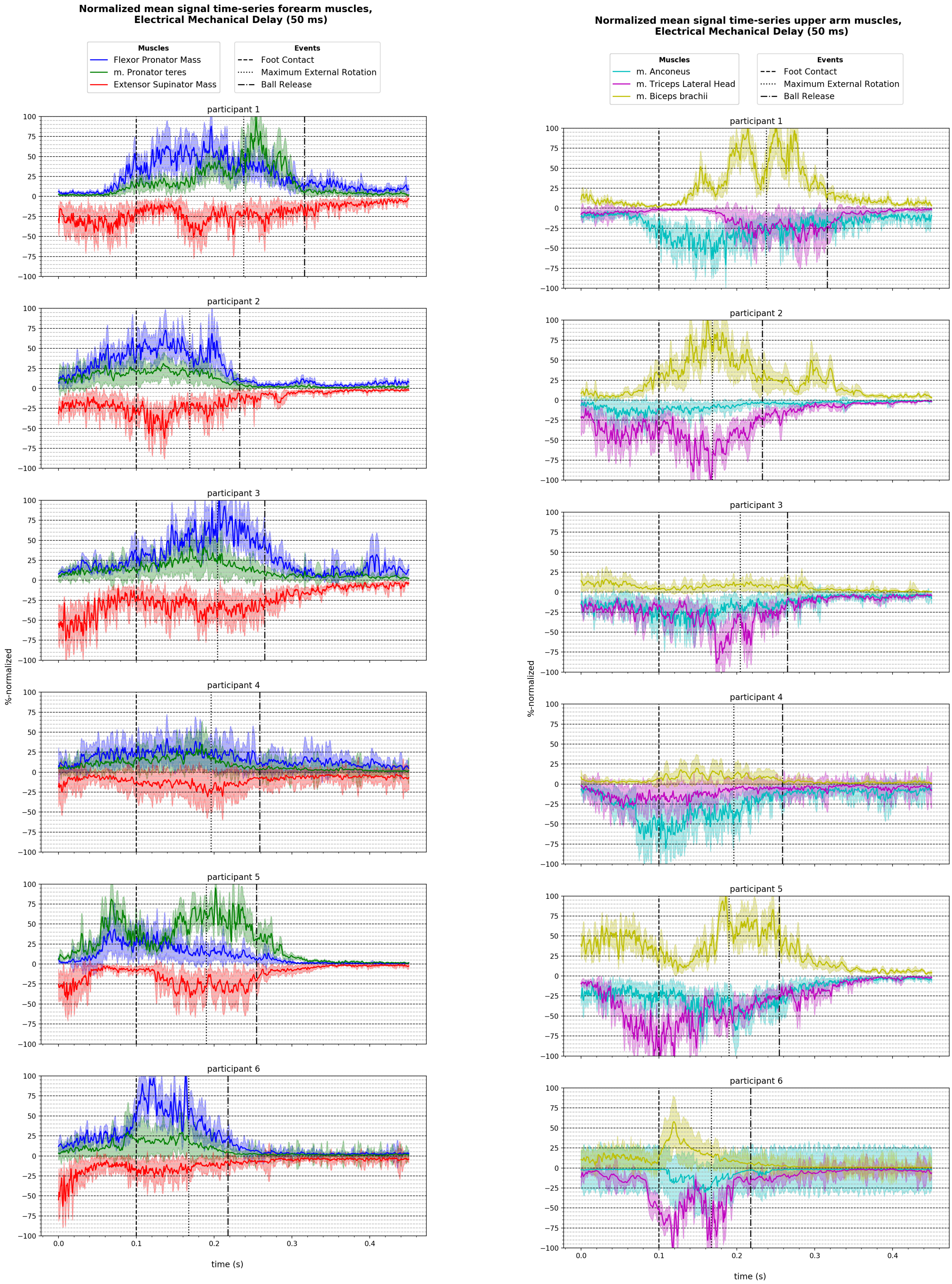


Figure 3.1: Group mean signal time-series and standard deviation with corrected EMD across the 6 participants, synchronized on the instance of foot contact. The Extensor Supinator Mass (ESM) is plotted to the negative side, to illustrate its opposite effect to the Flexor Pronator Mass (FPM) and m. pronator teres. The m. triceps lateral head and m. anconeus are plotted to the negative side, to illustrate its opposite effect to the m. biceps brachii.



(a) The forearm muscles activities for each individual participant. The Extensor Supinator Mass (ESM) is plotted to the negative side, to illustrate its opposite effect to the Flexor Pronator Mass (FPM) and m. pronator teres.

(b) The upper arm muscles activities for each individual participant. The m. triceps lateral head and m. anconeus is plotted to the negative side, to illustrate its opposite effect to the m. biceps brachii.

Figure 3.2: Mean signal time-series and standard deviation with corrected EMD across the performed pitches of the separate participant, synchronized on the instance of foot contact.

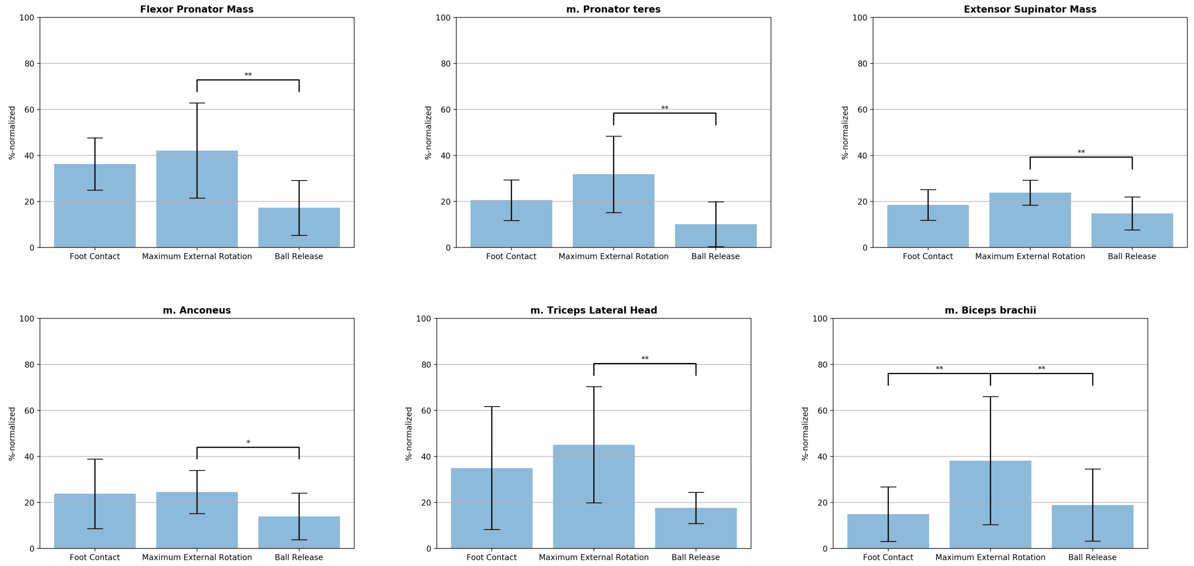


Figure 3.3: Means and standard deviations of the participants' 10ms mean muscle activity at (1) foot contact, (2) maximum external rotation and (3) ball release (mean ± SD (95% Confidence interval)), for each muscle separately. Asterisks '*' indicate significant difference p<0.05. Asterisks '**' indicate significant difference p<0.01.

3.2. Muscle activation ratio

A co-activation ratio was found 1.9 for both the forearm FPM:ESM muscle pair and the upper arm MTLH:MBB pair at MER with a standard deviation of 1.1 and 1.7, respectively (see figure 3.4). Compared to MER, a higher ratio is observed at FC (2.6 ± 1.3 and 2.1 ± 0.7, respectively) for both of these muscle pairs, whereas BR showed a lower ratio (1.5 ± 0.8 and 1.3 ± 0.6, respectively). The repeated measures ANOVA revealed only for the upper arm muscles pair a significant effect between the particular pitch events (F(1.439,120.885)=10.491, P<0.001). The post hoc test showed a significant difference between the instance of FC and MER for the m. triceps lateral head:m. biceps brachii pair. No significant difference was found between the MER and BR for the FPM:ESM pair.

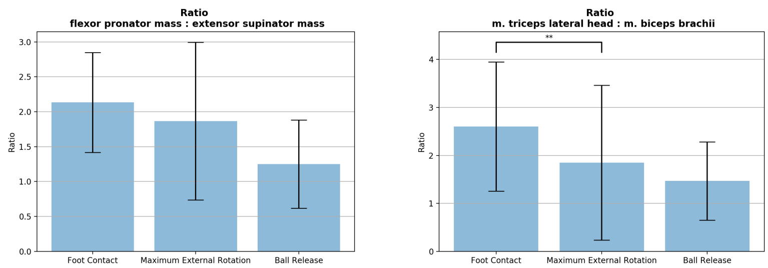


Figure 3.4: Mean muscle activation ratio's over all participants 10ms mean at (1) foot contact, (2) maximum external rotation and (3) ball release (mean ± SD (95% Confidence interval)). Asterisks '*' indicate significant difference p<0.05. Asterisks '**' indicate significant difference p<0.01.

4
Discussion

The aim of this study was to investigate whether the individual muscles around the elbow joint and the associated co-contraction show a significant muscle activity around the instance of maximum external rotation (MER) to compensate for the external valgus moment (EVM) during a fastball pitch. The results showed that each individual muscle shows peak muscle activity around the instance of MER, whereby in particular the FPM and m. triceps lateral head revealed high activity (42% and 45%, respectively) (figure 3.3). All muscle activities reduce significantly at BR in relation to MER for all investigated muscles. In addition, only the m. biceps brachii showed a significant higher muscle activity at MER compared to the instance of FC (38% and15%).

The observed peak FPM and MPT activity of 42% and 32% respectively at MER might be explained by its directly counteracting function to the peak EVM at the same instance, when compared to the low activity of these muscles and relative lower EVM at BR. A continuous FPM and MPT activity is found between FC and MER. The kinematic observation from the video recordings showed an increasing flexion angle slightly prior FC (see figure A.4 in the Appendix for a typical example of the elbow flexion angle throughout the pitch cycle). Therefore, the FPM and MPT activity at FC might be explained by a supporting role to terminate an elbow flexion movement around FC. The continuous FPM and MPT activity from FC till MER might be supported from an anatomical perspective as well as based on results from previous in-vitro studies. The FPM refers to the collection of muscles that collectively cross the medial side of the elbow joint, used for wrist, finger and elbow flexion and pronation. The MPT was incorporated separately from the FPM bundle in this research. The MPT origins at the medial supracondylar ridge of humerus and inserts at the lateral surface of the radius, initiating pronation of the forearm and elbow flexion. Bearing this in mind, the anatomical function of the FPM and MPT affirms the suggested supporting function of both muscles around the instance of FC to terminate a flexion movement. In-vitro research showed that the FPM group, except the MPT, partially or fully overlay the UCL and accordingly proved the FPM as significant contributor to the valgus stability by its direct effect of the counteracting tension [9, 22, 27, 30, 32]. The same studies documented that the MPT not overly the UCL but a valgus stabilizing function is still found, but not as much compared to the FPM. According the resulting continuous activity of the FPM and MPT till MER in this study, the previous in-vitro studies support the suggested directly compensating effect of both muscles to deliver a counteracting tension to the peak EVM around the instance MER.

The individual muscle activity data was used to assess the relative contribution of the forearm FPM:ESM and upper arm m. triceps lateral head (MTLH):m. biceps brachii (MBB) muscle pairs to investigate the indirect effect to counteract the EVM. The results showed a co-contraction ratio of 1.9 for either the FPM:ESM as the m. triceps lateral head (MTLH):m. biceps brachii (MBB) muscle pairs at the instance of MER, with no significant difference compared to the ratio at BR. The significant higher MTLH:MBB ratio at the instance of FC might be explained by the low EVM value at the instance of FC (see 1.1), while the MTLH probably terminates a extension moment to the elbow joint. Subsequently, the EVM peaks slightly after MER and the elbow extends rapidly between MER and BR. It is found that it takes only about 60 ms from approximately 80° elbow flexion at MER till full extension at BR for the measured participants in this research (see figure 3.2 for the time period and figure 2.2 and A.4 to observe the difference in elbow flexion). The rapid elbow extension induces an explosive active eccentric movement of the MBB and concentric movement of the m. triceps brachii. According the theorem of the muscle force-velocity relationship [18], eccentric contracting muscles can produce relatively more force with equal velocity compared to concentric contracting muscles (see figure 4.1). Therefore, the eccentric contracting MBB requires less activity to apply equal force onto the elbow joint from MER till BR compared to the concentric MTLH.

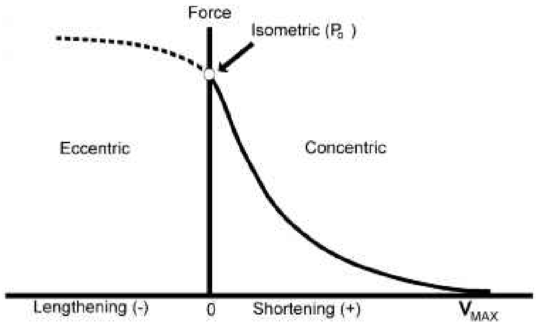


Figure 4.1: The skeletal muscle force-velocity curve.

The results of present research can to some extent be compared to previous EMG studies [10, 15, 31]. These studies averaged the signal over the pitch phases (see figure 1.4) and normalized the signal to MVC. Additionally, it is unknown from the documentation whether an EMD was applied in those studies. The results of previous and present study are composed in table 4.1, with the pitch event mean values from present study opposed to the adjacent pitch event values from previous studies. The averaged muscle activity in the late cocking and acceleration phase from previous research is compared to the mean activity value found around MER in present study. The FPM and MPT activity found in the late cocking phase of two of the previous studies relates to the results of present study at MER. However, two of previous studies showed very high activity for these muscles in the acceleration phase (104 and 120 %-MVC FPM and 85 %- MVC MPT activity) [10, 15]. In the same two study was a high ESM activity revealed in the late cocking and acceleration phase (ranging between 40 and 70 %-MVC), whereas the other study [31] observed moderate activity in both phases (± 25 %-MVC) similar to the present results at MER. The upper arm muscles revealed similar results in present study at MER to those from previous research [10, 15] in the late cocking phase, where previous research found a higher MTLH activity in the acceleration phase (89 %-MVC). The MBB continues moderate active from the late cocking phase till the acceleration phase in previous research (20 %-MVC), comparable to the observed value at MER. A high ESM activity (46, 37 and 59%) and a moderate activity (±20%) of the other muscles was found in the previous studies, whereas in present study the activity of the ESM (18%) was found to be moderate along with a high FPM (36%) and MTLH activity (35%) at FC. The low activity of BR of present study can be compared to the results in the follow-through of previous studies, where only one study found substantial high FPM (60 %-mvc) and m. triceps (42 %) activity [15].

The results obtained in previous research were less accurate compared to this study, lower sample frequencies were used (450 Hz compared to 2000 Hz in present study) and the signals were averaged over the pitch phases, leading to limited insight in the activation pattern around the instance of MER. Differences might be explained by the low accuracy of previous research. Despite the inconsistencies and limited methodology documentation of these relative old EMG studies, the results from literature indicates muscle activity in other studies and are not excessive different from current research. Additionally, the remaining m. anconeus (MA) on its own shows significant activity at FC and MER, indicating its support to compress the elbow joint and terminate an extension moment. However, the individual MA activity showed considerable differences between the participants (see 3.2) and the MA is never included in previous EMG studies, making it impossible to validate the results of present study. Conclusions about the contribution of the m. anconeus muscle should, therefore, be made cautiously.

In present study, equal EMD was applied to each muscle and participant involved using the assumed general delay of 50 ms for the upper extremity muscles [5]. Published values for the biceps and triceps brachii muscles are typically in the range of 15 to 60ms [5, 19, 21, 25]. For the forearm muscles a EMD of 30-70 ms is documented in literature [8, 25]. The specific EMD value may has influence on the timing of the actual applied force in a rapid movement like a baseball pitch. For instance, a smaller EMD will cause a shifts of the low activity at BR towards MER, causing lower FPM activity at MER and thereby resulting in a lower direct compensating effect of the FPM to the EVM compared to suggested in present study. Therefore, the reliability of current method of the generalized EMD value for application in subject specific

Muscle	**Literature** Pitch Phase	%-MVC Digiovine [10]	Sisto [31]	Glousman [15]	**Present research** Pitch Event	%-Normalized
FPM	Early cocking	24	17	24	FC	36
	Late cocking	45	29	47	MER	42
	Acceleration phase	104	17	120		
	Deceleration phase	76	no data	no data	BR	17
	Follow-through	27	13	60		
m. pronator teres	Early cocking	18	25	18	FC	21
	Late cocking	39	25	39	MER	32
	Acceleration phase	85	28	85		
	Deceleration phase	51	no data	no data	BR	10
	Follow-through	21	8	34		
ESM	Early cocking	46	37	59	FC	18
	Late cocking	69	25	73	MER	24
	Acceleration phase	40	22	43		
	Deceleration phase	35	no data	no data	BR	15
	Follow-through	23	24	33		
m. anconeus	Early cocking	no data	no data	no data	FC	24
	Late cocking	no data	no data	no data	MER	25
	Acceleration phase	no data	no data	no data		
	Deceleration phase	no data	no data	no data	BR	14
	Follow-through	no data	no data	no data		
m. triceps	Early cocking	17	no data	17	FC	35
	Late cocking	37	no data	37	MER	45
	Acceleration phase	89	no data	89		
	Deceleration phase	54	no data	no data	BR	18
	Follow-through	22	no data	42		
m. biceps brachi	Early cocking	22	no data	22	FC	15
	Late cocking	26	no data	26	MER	38
	Acceleration phase	20	no data	20		
	Deceleration phase	44	no data	no data	BR	19
	Follow-through	16	no data	26		

Table 4.1: Results of previous EMG-studies [10, 15, 31] and present study.

measurements needs further study. However, the assumed general value is sufficient for this specific research in the comprehensive approach to examine the muscle activation pattern during a fastball baseball pitch. Subsequently, whereas previous studies used a substantial lower sample frequency whereby the information remains limited, current research showed a reliable detailed muscle activation pattern to assess its timing and magnitude in accordance to the external valgus moment from FC till BR. Supplementary measurements are required to compensate for this bias to enhance the reliability of this research. Lastly, the pitch measurements have shown that some pitchers produce a higher mean muscle activity during the pitch in comparison to its maximum value from the MVC tests. It is questionable whether the assumed maximum muscle activity, to which the mean signal is normalized when it exceeds the maximum from the MVC tests, actually represents its real 100% activity. However, it was conceivable to use this method to indicate the activation variance among the measured muscles. Thereby, the EMG signal amplitudes does not tell us what the actual produced force and moment would be.

To gain more insight in the capacity of the muscles to compensate for the external valgus moment within individual pitchers, future research could look into the differences between the participants. This research only discussed the trends of muscle activation and ratios with respect to the external valgus moment, but the absolute values of the individual pitchers were not referred. The reason for this was the focus on the general capacity of the muscles to compensate for the external valgus moment. Although the absolute values were not analyzed, these results are still valuable in terms of analyzing the differences and its accompanied effects between the individual participants.

From a clinical point of view, the insights from present study can be used as reference data for clinicians and/or researchers who are interested in assessing the muscle activation pattern of a pitcher as support to predict and prevent UCL injuries in pitchers in the future. Identical measurement setups to the method of present study can be used by the physicians to investigate the muscle activity of individual pitchers. The results of present study can support the physicians and coaches to adapt the pitching technique on an individual level to avoid UCL injuries. As the muscle activity magnitude and timing varied between pitchers, future studies could be aimed at exploring the muscle activation patterns on an individual level to investigate individual differences and the accompanied causes and consequences. The investigation in the individual pitchers could help in understanding whether some pitchers might have less capacity to compensate for the external valgus moment by their muscles and thus are more prone to an UCL injury than others. Further research could study how changes in pitch technique could lead to a beneficial changes in the compensating capacity to the external valgus moment by the muscles.

5

Conclusion

The use of surface EMG in the fastball pitch measurements resulted in a conceivable prediction of the muscle activation pattern around the elbow joint according its capacity to compensate for the peak external valgus moment around the instance of maximum external rotation. A significant peak activity was found at maximum external rotation for all muscles, compared to the instance of ball release. The parallel activity of the flexor pronator mass and m. pronator teres at maximum external rotation enhances the suggested compensating effect to the external valgus moment by its directly counteracting force. Furthermore,the ratios between the flexor pronator mass:extensor supinator mass and m. triceps lateral head: m. biceps brachii muscle pairs support a co-contracting activity at MER. The proposed indirect effect of the co-contraction in the forearm and upper arm might compensate for the external valgus moment by compressing the elbow joint together. Lastly, it might be considerable that the m. anconeus supports the elbow compression at the instance of the peak valgus moment. However, this study showed considerable differences between participants for the m. anconeus, making that the function of the m. anconeus in the fastball baseball pitch is still debated based on this study.

This study provides evidence that the muscles around the elbow joint can compensate for the external valgus moment during a fastball pitch. These results provide possibilities for using sEMG to assess the muscle activation pattern of individual pitchers as support to predict and prevent UCL injuries in pitchers in the future.

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A

Appendices

A.1. Methodology

A.1.1. Maximum Voluntary Contraction: Exercises

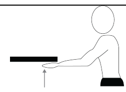
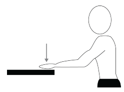
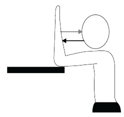
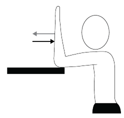
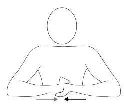
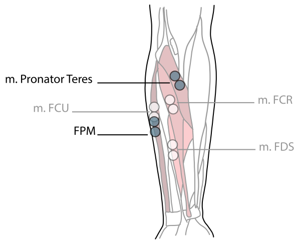
Muscle group	Exercise	Illustration
Forearm Flexors	Seated or kneeling position in front of the table. With the forearm in approximately 90 °with respect to the upper arm. Participant performs a wrist flexion by pushing the handpalm against the bottom of the table. The table functions as static resistance. The table is held down to resist the participant of lifting the table.	
Forearm Extensors	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. The researchers applies a static resistance against the forearm while the participant performs an elbow flexion.	
m. Triceps 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. The researchers applies a static resistance against the forearm while the participant performs an elbow Extension.	
m. Pectoralis Major	Stand up position with the shoulders and elbows in an 90 °angle. The hands meet in front of the chest, with the handpalms against each other. The fingertips of the throwing arm faces to the chest and applies force to the static resistance of the other handpalm.	

Table A.1: MVC exercise description. All exercises are performed with the participant's throwing arm. The gray arrow indicates the applied force direction of the participant. The black arrow indicates the direction of resistance.

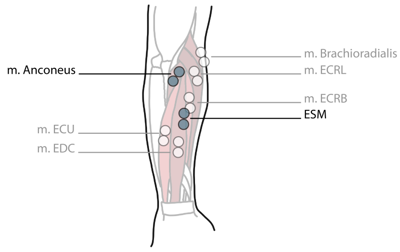
A.1.2. Electromyography sensor positioning

Portion	Muscle	EMG Location	EMG orientation
Forearm anterior side	Flexor Pronator Mass	At 1/3 between the medial side of the elbow and wrist.	In the direction of the line between the medial epicondyle of the humerus and the pisiform bone (medial side of the wrist).
	m. Pronator Teres	1/3 distal from the elbow joint in between the medial and lateral epicondyle of the humerus.	In the direction of the line between the humeral head (medial side of the elbow) and the lateral surface of the radius (cross the forearm diagonally).
Forearm posterior side	Extensor Supinator Mass	At the posterior side of the forearm at 1/3 distal and medial from the lateral epicondyle of the humerus (lateral side of the elbow joint).	In the direction of the line between the lateral supracondylar ridge of the humerus and the middle posterior side of the wrist.
Upper arm anterior side	m. Biceps brachii	On the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit.	In the direction of the line between the acromion and the fossa cubit.
Upper arm posterior side	m. Triceps long head	Electrodes need to be placed at 50 % on the line between the posterior crista of the acromion and the olecranon at 2 finger widths lateral to the line.	Parallel to line between the posterior crista of the acromion and the olecranon.
	m. Anconeus	Parallel to and below the olecranon on the radial side.	In line between the lateral epicondyle of the humerus and the ulna.
Chest	m. pectoralis major	At the height of ½ of the sternum and in the middle of the sternum and the armpit.	Parallel to the line between the distal part of the sternum and the lateral lip of the bicipital groove of the humerus (armpit).

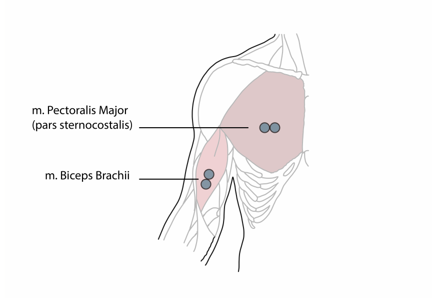
Table A.2: Electromyography sensor location and orientation per muscle described (table created by author based on [1]).



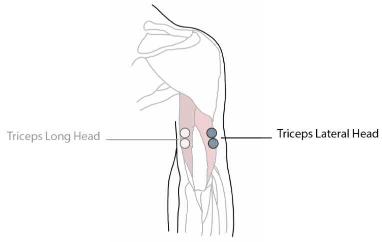
(a) EMG electrodes positioning at the flexor pronator mass muscles, anterior view left forearm.



(b) EMG electrodes positioning at the extensor supinator mass muscles, posterior view left forearm.



(c) EMG electrodes positioning at the m. biceps brachii and m. pectoralis major, anterior view right upper arm and chest.



(d) EMG electrodes positioning at the m. Triceps Lateral Head and m. triceps lateral head, posterior view right upper arm.

Figure A.1: Electromyography Sensors Positioning and Orientation (figure created by author).

A.1.3. Data analysis flow

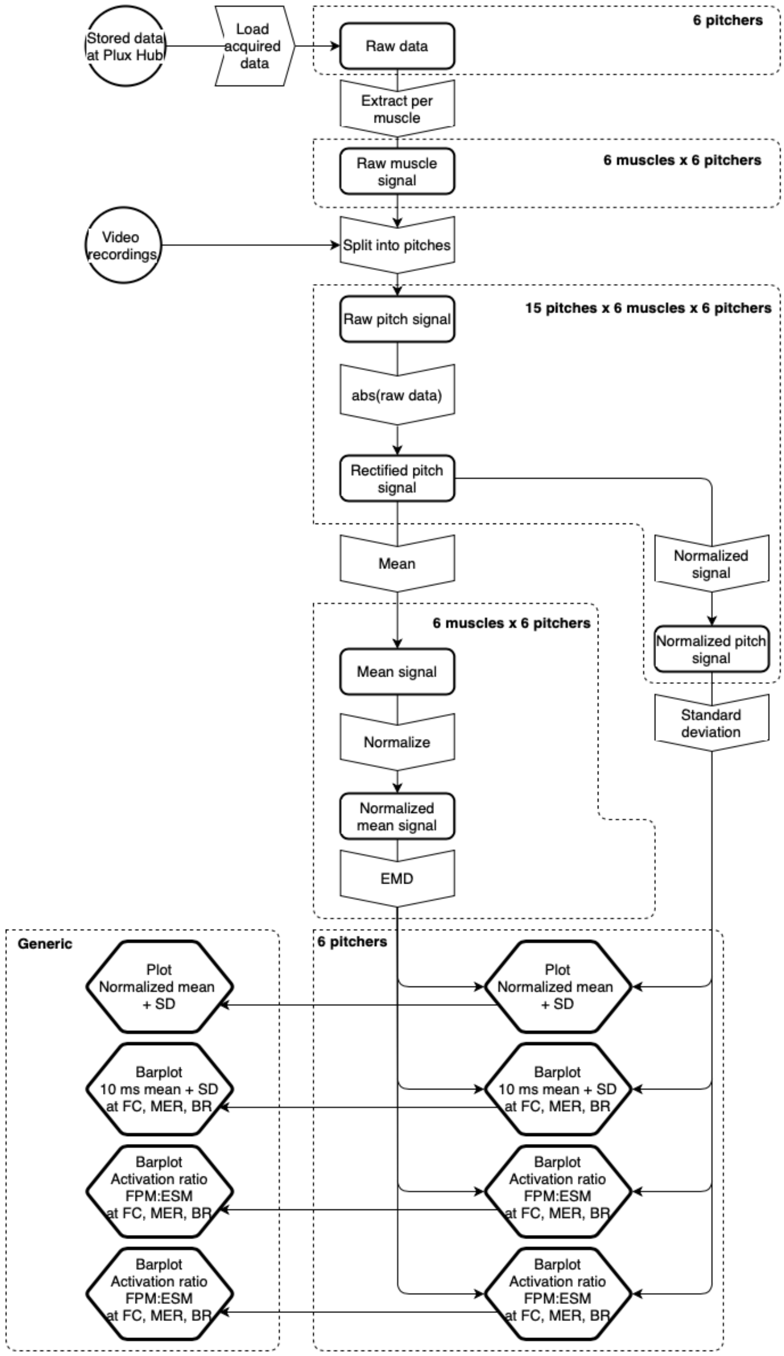


Figure A.2: Data analysis procedure flow

A.2. Results

A.2.1. Rectified EMG signal

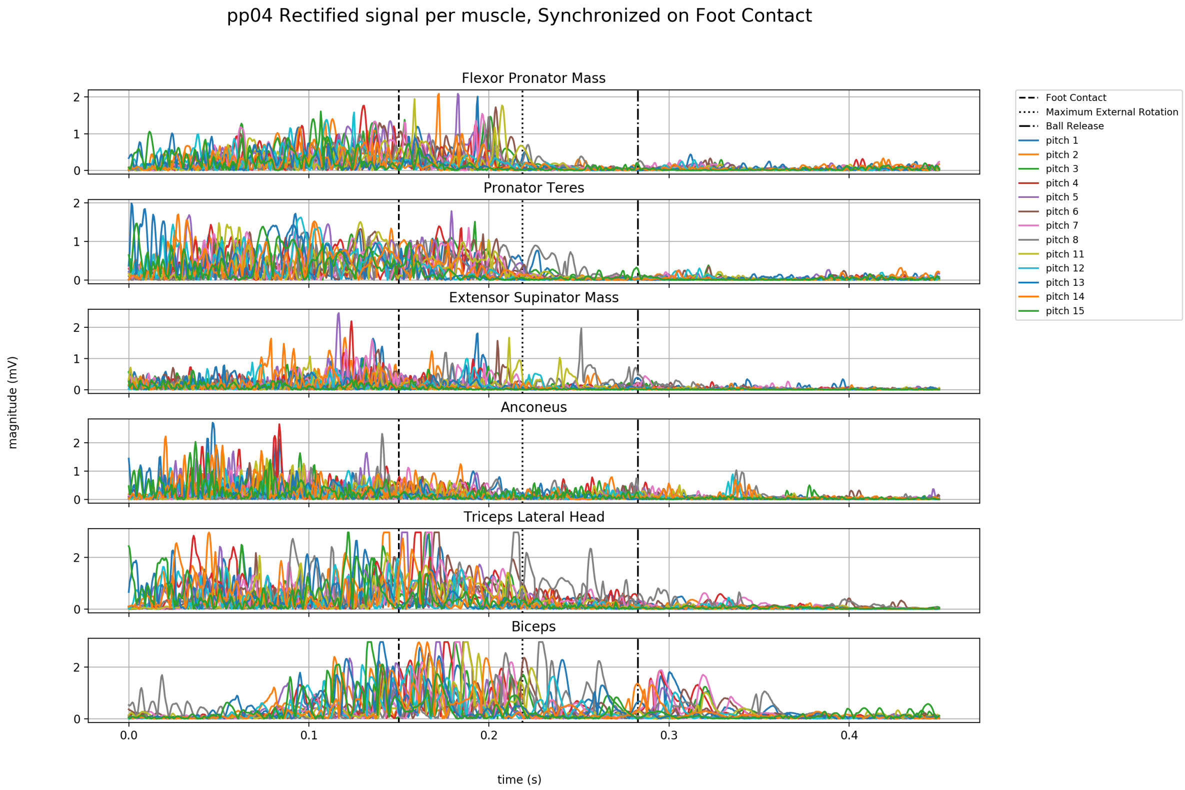


Figure A.3: Typical example of the rectified raw EMG signal.

A.2.2. Mean normalized muscle activity at FC, MER, BR

	Pitch Events FC pp01	pp02	pp03	pp04	pp05	pp06	Mean
A. Norm. Muscle Activation (%)							
Flexor Pronator Mass	39.4± 14.5%	47.3± 21.2%	33.2± 40.6%*	23.2± 14.0%	25.2± 8.2%	53.7± 25.8%*	36.99±25.16%
m. Pronator Teres	14.8± 4.7%*	21.7± 12.0%	13.1±8.3%	14.4± 11.4%	38.9± 23.9%	20.4± 11.3%	20.564 ± 15.67%
Extensor Supinator Mass	21.1± 6.3%	28.5± 16.4%	22.1± 14.1%	13.3± 8.2%	7.6± 3.3%	18.3±7.3%	18.48± 12.06%
m. Anconeus	28.6± 6.6%	13.3± 6.3%	23.0± 9.9%	54.4± 30.3%	25.2± 9.9%	1.8± 0.2%	24.38± 21.22%
m. Triceps Lateral Head	1.8± 0.9%	151.7 ± 119.5%*	18.5± 9.0%	16.9± 10.1%	285.3 ± 117.4%*	65.2± 32.5%*	89.89± 121.89%
m. Biceps Brachii	4.5± 1.7%*	105.6 ± 64.0%*	4.5± 4.4%	6.6± 7.9%	99.8± 81.3%*	13.6± 10.2%	39.11± 10.15%
B. Muscle Activation Ratio							
FPM-MPT	2.8± 1.1	3.0 ± 2.7	2.3± 1.7	2.2± 1.6	1.0± 1.0	3.4± 2.0	2.5± 2
Tri-Anc	0.1± 0.0	11.6± 6.6	0.9± 0.5	0.4± 0.3	12.5± 6.8	36.5± 20.4	10.3 ± 15.7
FPM-ESM	2± 0.9	2.5 ± 2.3	0.7± 0.4	2.1± 1.5	3.8± 1.9	3.1± 1.7	2.4± 1.8
PT- ESM	0.7± 0.3	1.0 ± 0.8	0.7± 0.4	1.1± 0.5	5.4± 3.1	1.1± 0.7	1.7± 2.1
Tri-Bic	0.5± 0.3	4.5 ± 9.3	11.4± 13.5	5.7± 6.3	6.5± 7.2	7.3± 6.7	6± 8.6
Anc-Bic	7.2± 3.0	0.3 ± 0.5	15± 18.2	12.9± 9.7	0.6± 0.8	0.5± 1.3	6.1±10.3
C. Elbow Angle (°)							
Flexion angle	125°	55°	80°	75°	90°	106°	88.5 ± 22.4°

	Pitch Events MER pp01	pp02	pp03	pp04	pp05	pp06	Mean
A. Norm. Muscle Activation (%)							
Flexor Pronator Mass	36.6± 16.8%	38.6± 18.3%	85.7± 42.2%	19.3± 13.6%	15.3± 7.1%	62.9± 32.3%*	43.07±34.43%
m. Pronator Teres	44.5± 26.4%*	21.37.8%	23.712.8%	15.2± 14.3	66.2± 21.1%	21.5± 16.0%	32.06± 24.64%
Extensor Supinator Mass	23.4± 13.4%	21.6± 16.7%	35.4± 19.4%	19.1± 12.1%	23.8± 13.0%	14.4± 9.0%	22.94± 15.35%
m. Anconeus	25.3± 15.1%	8.6± 3.0%	19.0± 6.5%	34.6± 27.8%	45.0± 21.5 %	14.5± 19.0	24.49± 21.15%
m. Triceps Lateral Head	25.3± 16.7%	270.9 ± 121.2%*	38.2± 22.8%	5.3± 5.5%	165.4 ± 67.1%*	84.8± 53.5%*	98.3 ± 111.24%
m. Biceps Brachii	64.6± 55.3%*	289.7 ± 93.0%*	12.2± 4.3%	11.2± 8.3%	201.5 ± 133.0%*	15.2± 11.0%	99.07± 128.48%
B. Muscle Activation Ratio							
FPM-MPT	1.3 ± 1.5	2.2± 1.9	4.8 ± 4.1	1.8± 1.3	0.2 ± 0.1	4.0 ± 2.7	2.4 ± 2.7
Tri-Anc	1.5 ± 1.4	39.2± 30.9	2.3 ± 1.5	0.2. ± 0.1	5.6 ± 6.0	24.9± 27.1	12.3 ± 22.1
FPM-ESM	2.6 ± 2.4	2.5± 1.6	1.0 ± 1.0	1.2± 1.1	0.9 ± 0.6	6.1 ± 4.9	2.4 ± 3.0
PT- ESM	2.5 ± 2.3	1.6± 1.3	1.0 ± 1.0	1.8± 1.1	3.8 ± 2.4	0.9 ± 1.0	2.0 ± 1.9
Tri-Bic	0.6 ± 0.4	0.9± 0.3	3.6 ± 3.0	1.1± 2.1	1.2 ± 0.9	8.0 ± 7.1	2.6 ± 4.1
Anc-Bic	0.6±0.4	0± 0.0	1.7 ± 0.8	6.8± 9.4	0.4 ± 0.3	1.3 ± 1.5	1.8 ± 4.4
C. Elbow Angle (°)							
Flexion angle	60°	60°	86°	80°	82°	89°	76.2° ± 11.8°

	Pitch Events BR pp01	pp02	pp03	pp04	pp05	pp06	Mean
A. Norm. Muscle Activation (%)							
Flexor Pronator Mass	16.3± 6.7%	12.7± 8.9%	38.4± 31.0%	14 ± 14.2%	9.5± 8.5%	21.2 ± 20.4%*	18.67±19.27%
m. Pronator Teres	9.9± 8.0%*	4.5± 5.0%	5.8± 4.8%	4.9± 3.5%	32.7± 23.7%	4.7± 2.2%	10.41 ± 14.56%
Extensor Supinator Mass	16.4± 10.8%	10.2± 13.0%	32.5± 17.0%	7.5± 3.8%	17.3± 10.1%	9.4± 6.3%	15.55 ± 13.65%
m. Anconeus	22 ± 12.3%	3.7± 2.9%	12.9± 11.3%	18.9 ± 20.4%	39.1± 32.7%	4.1± 8.0%	16.80 ± 20.92%
m. Triceps Lateral Head	22.7± 12.4%	60.6± 33.7%*	14.4± 8.9%	5.8± 5.5%	97.9± 51.5%*	20.3 ± 27.2%*	36.93 ± 42.46%
m. Biceps Brachii	33.4± 28.7%*	76.1± 62.0%*	11.8± 9.6%	4.4± 4.3%	186.5 ± 125.4%*	4.5± 1.9%	52.79 ± 86.40%
B. Muscle Activation Ratio							
FPM-MPT	3.3± 4.0	4.8± 4.1	8.2± 6.0	2.8± 2.6	0.5± 0.7	5.1± 5	4.1± 4.6
Tri-Anc	1.5± 1.2	28.8± 34.0	1.9± 1.4	0.4± 0.3	3.6± 2.3	10.5 ± 13.4	7.8± 17.7
FPM-ESM	1.4± 1.0	1.8± 1.0	0.2± 0.1	3.3± 5.0	0.8± 1.2	3.4± 3.9	1.8±2.9
PT- ESM	0.9± 0.8	0.6± 0.6	0.2± 0.1	0.6± 0.4	2.5± 2.5	0.9± 1.0	1± 1.4
Tri-Bic	1.7± 2.5	1.5± 1.6	4.4± 8.7	2.6± 4.7	0.7± 0.5	4.4± 4.6	2.6± 4.7
Anc-Bic	1.3± 1.6	0.1± 0.2	5.3± 11.4	9.4± 17.9	0.3± 0.5	1.2± 2.1	2.9± 9.1
C. Elbow Angle (°)							
Flexion angle	20°	30°	15°	25°	20°	5°	19.2° ± 7.9°

Table A.3: Overview of results. A) Individual Muscle Activation (mean ± SD (95% Confidence interval). Each value represents the mean normalized muscle activity of 10ms around the concerned pitch event. The muscle activity was normalized to a reference value that intents to reflect 100% muscle activity. Primarily, the reference value was obtained as the average of the three maximums of the MVC test. When the peak of the 15 pitch averaged signal showed higher muscle activity than this reference value, the peak of the 15 pitch averaged signal was obtained as 100% muscle activity reference value to which the mean EMG signals where normalized. * denotes values that were normalized to its peak averaged signal. B) Muscle activation ratios (Mean ± SD (95% Confidence Interval). The ratios were calculated by dividing the two normalized mean muscle activity values. C) Elbow flexion angle. 0° represents a full elbow extension. The flexion angles were estimates based on the video recordings.

A.2.3. Statistics

Pitch Event Transition	FPM F(1.827,153.496)=31.592, P<.0005	PT F(1.868,156.942)=46.077, P<.0005	ESM F(1.943,163.227)=8.092, P=.001	Anconeus F(1.886,158.437)=7.036, P=0.001	Triceps F(1.674,140.629)=31.972, P<.0005	Biceps F(1.792,150.547)=29.029, P<.0005
FC-MER	0.273	0.314	0.074	1.000	1.000	<.0005
MER-BR	<,0005	<.0005	0.001	0.013	<.0005	<.0005
FC-BR	<.0005	<.0005	0.258	0.002	<.0005	0.302

Table A.4: Pairwise comparison individual muscles

Pitch Event Transition	FPM-PT F(1.625,136.494)=9.885, P<.0005	Tric-Anc F(1.778,149.377)=2.445, P=.097	FPM-ESM F(1.811,152.144)=1.715, P=.186	PT-ESM F(1.83,153.846)=11.846, P<.0005	Tri-Bic F(1.439,120.885) = 10.491, P<.0005	Anc-Bic F(1.669, 140.199)=7.058, P=.002
FC-MER	1.000	0.805	1.000	0,391	0.002	<.0005
MER-BR	0.003	0.181	0.460	0,003	1.000	0.089
FC-BR	0.002	0.588	0.356	<.0005	0.003	0.838

Table A.5: Pairwise comparison activation ratios

A.2.4. Elbow flexion angle

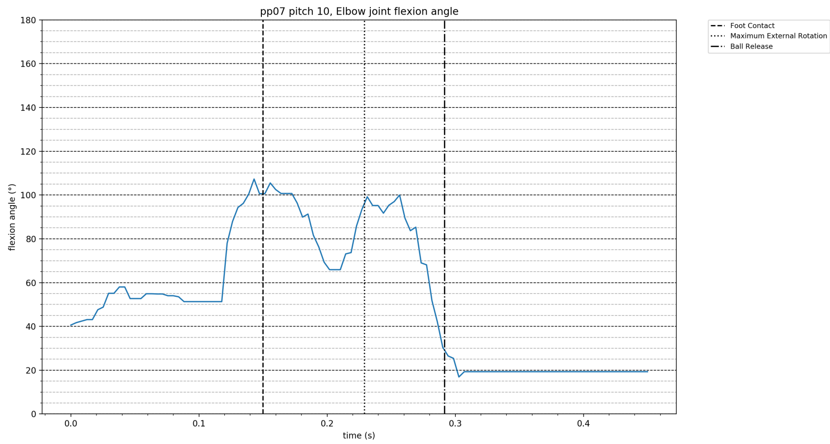


Figure A.4: Typical example of the elbow flexion angle during the fastball pitch.