Lower extremity kinematic and temporal changes in adolescent baseball pitchers during a simulated game

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Abstract

Aim: To investigate whether adolescent baseball pitchers change lower extremity kinematic and temporal parameters during a simulated game, which may affect performance outcomes. **Method:** Twelve male adolescent pitchers (14 – 16 years) threw 90 pitches (6 sets of 15 pitches) from an artificial mound towards a pitching net. Angular displacements, angular velocities and temporal parameters at the hip, knee and ankle of the trailing and leading legs were collected throughout the pitching cycle. Dependent variables were analysed from the balance position through to maximal internal rotation of the shoulder. Performance outcomes of ball velocity and pitching accuracy were also recorded. The last five pitches of the second and final sets were compared to determine whether changes in the pitching mechanics and performance outcomes had occurred by the end of the simulated game. **Results:** Pitchers assumed a less upright posture and the leading leg was not raised as high at the balance position in the final set. Throughout stride phase, pitchers decreased maximal hip extension and ankle plantarflexion displacements in the trailing leg. Additional decreases in the maximal angular velocities for hip abduction and knee extension were seen throughout the stride phase in the final set. Foot contact occurred earlier in the final set, resulting in decreased hip flexion and increased hip abduction in the leading leg. No kinematic differences were observed between sets at ball release. Ball velocity and pitching accuracy decreased in the final set. **Conclusion:** Kinematic differences in the lower extremities suggest that lower extremity musculature may have been affected by fatigue by the end of the simulated game. Consequently, pitchers may have produced less forward momentum during the final set of pitches, which could have contributed to the decreased ball velocity. The altered balance position seems to be the underlying factor for the subsequent changes in the lower extremity pitching mechanics. Therefore, the leading leg hip flexors and the trailing leg hip and knee extensors may require strengthening to maintain the balance position. Additional strengthening of the ankle plantarflexors would assist the hip and knee in producing consistent propulsive forces during the stride phase throughout a game.

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1. Introduction

The fastball is the most common type of pitch used for baseball pitching, particularly among youth and adolescent pitchers [1]. The fastball is popular as pitchers can generate the fastest ball velocity with this pitch type [2, 3]. To achieve ball velocities of up to 145km.h^{-1}, pitchers use a kinetic chain to transfer the energy generated by each segment to the distally adjacent segment [4-6]. Therefore, the kinetic chain requires coordinated sequencing of all body segments to effectively accelerate the ball. The kinetic chain begins at the lower extremities as the leading leg is lowered and the trailing leg drives off from the pitching mound towards the home plate [7, 8]. This initiates the generation of forward linear and angular momentum of the body. Upon lead foot contact, energy is then transmitted up the body to the pelvis, trunk, upper extremities and through to the ball [7, 9]. Pitchers also exploit the summation of speed principle to produce greater angular velocities at the distal joints, thus improving ball velocity [10]. To effectively utilise the summation of speed principle, each segment must initiate movement upon the preceding segment achieving its maximal angular velocity. Accordingly, temporal parameters have been identified as important factors influencing pitching performance [5, 11].

Numerous studies have investigated the upper extremities, pelvis and trunk during baseball pitching and their influence on ball velocity [12-15]. While the lower extremities have been included in these studies, a more comprehensive understanding of the lower extremities during the pitching motion is required. Milewski and colleagues have reported normative lower extremity kinematic data for adolescent pitchers [16]. However, the participants did not pitch from a pitching mound and the authors failed to report the joint kinematics throughout the wind-up and stride phases. Pitchers use the wind-up phase to move their body into an optimal starting position from which to initiate the drive towards the home plate (i.e. the balance position). Therefore, analysis of the pitching motion should also include the balance position as it sets up the pitching motion and the sequencing of movements in the subsequent phases [4, 6].The stride phase is then used to initiate the production of kinetic energy in the direction of the home plate in preparation for generating rapid angular velocities in the throwing arm later in the pitching cycle [7, 8]. As the lower extremities initiate the drive towards the home plate, the stride phase is also important in the analysis of the lower extremities.

Pitchers generate linear and angular momentum to accelerate the ball during baseball pitching. Parameters reflecting the forward momentum of the body throughout the pitching cycle have been investigated in relation to ball velocity. These include stride length, changes in the magnitude of knee flexion between foot contact and ball release and the knee extension velocity at ball release [3, 14, 17-21]. Although greater forward momentum is generated when using a longer stride length, it is more physiologically demanding, which may cause an early onset of fatigue [22, 23]. Conversely, shorter stride lengths suggest that less forward momentum has been generated, which may result in decreased ball velocities. However, previous studies have presented conflicting results regarding the relationship between stride length and ball velocity [14, 15], suggesting that further investigation is required. The differences in knee extension and the knee extension angular velocity at ball release are more consistently observed among pitches of different ball velocities. Faster ball velocities have been observed when the knee extends after foot contact and when pitchers generate a greater knee extension angular velocity at ball release [2, 3, 14]. As the shank maintains a relatively upright position during the arm acceleration phase [16], knee extension reflects the amount of forward momentum of the upper body after foot contact.

Previous research has observed that pitchers remained in a more vertical position and experienced more knee flexion at the instant of ball release and a decreased magnitude of maximal shoulder external rotation with fatigue [20, 24]. These kinematic responses to fatigue suggest the ability to produce forward momentum was reduced, which would presumably contribute to decreased ball velocities. Limited research has investigated the effect of extended play on pitching mechanics and performance outcomes, thus requiring further investigation. Movements throughout the pitching motion are largely dependent on each other. Therefore, it is important to identify any changes made to the pitching mechanics in the early phases of the pitching cycle that may result in subsequent changes to the pitching mechanics later in the pitching cycle. As the lower extremities are the first contributors to the kinetic chain, the aim of this study was to identify whether changes in lower extremity kinematic and temporal parameters and performance outcomes were experienced as adolescent pitchers progressed through a simulated game.

Aims for primary outcomes:

1. To investigate whether adolescent baseball pitchers change the lower extremity kinematics while pitching during a simulated baseball game.

Hypothesis 1a: Pitchers would change the angular displacements at the balance position in the final set of the simulated game.

Hypothesis 1b: In the leading leg, pitchers would exhibit differences in knee extension at ball release and the knee extension angular velocity throughout the acceleration phase at the end of the simulated game.

Hypothesis 1c: Pitchers would change their stride length in the final set of the game.

Hypothesis 1d: Pitchers would exhibit differences in the maximal angular velocities produced throughout the stride phase during the pitches of the final set.

2. To investigate whether temporal parameters of the pitching mechanics changed during a simulated baseball game.

Hypothesis 2: In the final set, pitchers would change the timing of maximal angular velocities in the trailing leg during the stride phase.

3. To investigate whether the variability of the balance position kinematics was altered over the duration of a simulated game.

<u>Hypothesis 3:</u> Pitchers would exhibit increased variability of the angular displacements at the balance position in the final set of the simulated game.

Aims for secondary outcomes:

1. To investigate whether performance outcomes (i.e. ball velocity and pitching accuracy) for baseball pitching change over the duration of a simulated game.

<u>Hypothesis 1:</u> Differences in the ball velocity and pitching accuracy would be evident in the final set of the simulated game compared to baseline performance.

2. Literature review

There are various different types of pitches used in baseball, each serving a different purpose. The fastball is used for its speed and is the most common pitch type, especially among youth and adolescent pitchers [1, 2]. With a fastball pitch, professional pitchers can generate ball velocities of approximately 145 km.h^{-1} [4, 5]. Other pitch types, otherwise known as breaking pitches, are used to manipulate the trajectory of the ball by applying spin to the ball. Some breaking pitch types include the curveball and slider among others. These breaking pitch types have been discouraged in youth pitchers as they are associated with an increased risk of shoulder and elbow pain [25]. However, more recent research has observed greater torques and compressive forces at the shoulder and elbow during the fastball pitch than the curveball or change-up (an off-speed pitch) in youth pitchers [3]. Previous studies have compared the pitching mechanics between pitchers of different skill levels [14, 17, 18] and between different pitch types [2, 3, 26, 27]. However, the research has largely focused on the relationships between the fastball pitching mechanics and ball velocity or risk of injury, due to the high incidence of shoulder and elbow injuries [4, 6, 12, 13, 16, 28-32].

2.1. The pitching cycle

In the analysis of baseball pitching, the pitching cycle has typically been broken down into six phases using events that occur throughout the pitch to define each phase. The events used to define each phase are generally consistent between studies, with only slight differences in the definitions of some events. The six phases include the wind-up phase, stride phase, arm cocking phase, arm acceleration phase, arm deceleration phase and follow-through phase.

2.1.1. Wind-up phase

The wind-up phase is the first phase of the pitching cycle. This phase starts at the initiation of movement and ends just before the pitcher begins to move their body towards the home plate. The event that signifies the end of the wind-up phase varies between studies. Previous studies have either used the balance position to identify the end of the wind-up [6, 33], or when the throwing hand is removed from the glove of the non-throwing hand [4, 24, 34]. However, limited research has investigated the pitching mechanics during this phase or at either of these events that terminate the wind-up phase [8, 13]. The balance position may be a more suitable event to end the wind-up phase as the body begins to initiate the drive towards the home plate prior to the hands separating [8]. The duration of this phase is highly variable due to individual differences in technique and whether the pitcher is using a full wind-up technique or starting from the stretch position [4]. Regardless of the differences in technique, the primary goal of this phase is to set up a good starting position and rhythm for the pitcher [4, 6]. Consistent preparation for the pitching motion may help with coordination and sequencing of the subsequent movements leading up to ball release.

Pitchers generally start the wind-up from a position where their whole body is facing the home plate. The ball is held in the throwing hand, which is concealed in the glove of the non-throwing hand. The ipsilateral leg relative to the throwing arm is the trailing leg and the contralateral leg relative to the throwing arm is the leading leg. Using the contralateral leg as the leading leg enables greater rotation of the pelvis and trunk, which assists in achieving faster ball velocities [5]. Once the wind-up phase is initiated, the trailing foot externally rotates approximately 90 degrees so that it is parallel to the pitching rubber [8, 35]. The upper body also rotates away from the home plate about the trailing leg to set up the drive towards the home plate. Rotating the body away from the home plate increases the potential to generate kinetic energy [4]. To further contribute to the potential to generate energy, the leading leg is lifted up and across the body as the leading hip flexes and slightly adducts [4]. The resulting position is called the balance position, which is typically when the leading knee reaches its maximal height [6]. The balance position has also been defined as when the thigh of the leading leg is parallel to the ground [8]. However, some pitchers may raise their thigh higher or lower than a position that is parallel to the ground, suggesting the former definition may be more appropriate. At the balance position, the body weight is now shifted to the trailing leg and the vertical ground reaction force (GRF) is approximately equal to 100% body weight (BW) [7, 8]. From this position, the pitcher is ready to drive the body towards the home plate.

While pitching is most commonly analysed using a full wind-up, some pitchers begin the pitching action from the stretch position. The stretch position is used to shorten the duration of the wind-up phase by starting the wind-up from a position where the body is already rotated 90 degrees away from the home base [3, 4]. No kinematic or temporal differences have been observed between foot contact and ball release when pitching from the stretch position compared to using the full wind-up [3, 4]. Additionally, there were no clinically significant differences observed in ball velocity when using either of these two starting positions [2-4]. However, the GRFs have been compared between a fastball with a full wind-up and a fastball using the stretch position. A greater peak vertical GRF was observed under the trailing leg during the stride phase when using a full wind-up [8]. Conversely, the vertical GRF was greater during the fastball from the stretch position at foot contact [8].

2.1.2. Stride phase

The stride phase occurs between the balance position and the instant of leading foot contact [4, 6]. The approximate duration of this phase is between 0.50 - 0.75 seconds [36]. Pitchers use this phase is to generate linear velocity of the body towards the home plate, which is initiated by the lower extremities [4-8]. A run up is utilised in many throwing activities, such as javelin throwing or cricket bowling. The run up is used to increase the kinetic energy of the body to transfer to the object being thrown [14, 37]. Javelin throwers can achieve linear velocities of their centre of mass of up to 7 $m.s^{-1}$ [37], while cricket bowlers achieve linear velocities of approximately 5.5 $m.s^{-1}$ [38]. However, a run up is not used for baseball pitching, highlighting the importance of recruiting all body segments to contribute to the generation of kinetic energy throughout the stride phase. Therefore, pitchers must ensure the body is moved into an ideal balance position that will optimise the use of all body segments to generate energy throughout the stride phase. Pitchers can generate peak linear velocities of approximately 2.1 – 2.8 $m.s^{-1}$, which occurs about 0.02s prior to foot contact [14, 39].

From the balance position, the pitcher begins to unwind and drive the body towards the home plate. Accordingly, the stride phase is also used to initiate the production of angular momentum as the pelvis and trunk begin to open up towards the direction of the home plate. It has previously been debated whether this movement is a controlled fall or a maximal effort push off [8]. The controlled fall theory suggests that the pitcher moves their body so that the centre of gravity passes over the base of support towards the direction of the home plate to initiate movement. The pitcher may then rely on the downward slope of the mound to help generate a larger braking force. Conversely, the push off theory suggests the pitcher relies on the trailing leg to drive the body forward. The magnitudes of the propulsive GRFs in the vertical and anterior directions were approximately 1.10 BW and 0.55 BW respectively [7, 8]. These GRF values suggest that the movement towards the home plate is more than just a controlled fall. However, Campbell et al [36] assessed muscle activity of the lower extremities using electromyography. They observed a 'ramping' effect in the muscle activity of the leg extensor muscles in the trailing leg throughout the stride phase, suggesting greater muscle activity occurred later in the stride phase. Therefore, pitchers may initially use a controlled fall prior to generating the propulsive forces to ensure that the push-off is directed towards the home plate rather than in the vertical direction. The peak propulsive GRFs occurred just prior to foot contact, which is approximately when peak linear velocity of the pelvis occurs [7, 8, 14]. While the trailing leg propels the body forward, the hands separate and the ball is removed from the glove. The shoulders begin to horizontally abduct and the elbow begins to extend as the arm moves posteriorly [4, 6, 8]. Pitchers then flex the elbow as the shoulder begins to abduct.

The wind-up and stride phases are often excluded from analysis [3, 14-16, 28]. However, more research should analyse these phases and the balance position due to their importance in setting up the pitching motion and generating linear and angular momentum prior to foot contact.

2.1.3. Arm cocking phase

The arm cocking phase begins at lead foot contact and continues through to maximum external rotation of the shoulder [4, 6, 28, 33]. Studies often describe this event as maximum external rotation of the glenohumeral joint. However, these studies have only investigated the shoulder as the movement of the humerus relative to the trunk, which would be confounded by trunk flexion and movements of the scapulothoracic joint. After foot contact occurs, the pitching action leading up to ball release is more rapid as the duration of the arm cocking phase is only 0.10 to 0.15 seconds [36]. The arm cocking phase is used to move the throwing arm into an optimal position from which to accelerate the ball. The shoulder horizontally abducts and externally rotates, positioning the ball further away from the home plate to increase the potential to generate energy in the arm and ball. While the arm is cocking, the pelvis and trunk rotate towards the home plate to produce a lag between the trunk and throwing arm. This lag produced between the body segments is used to enhance the external rotation of the shoulder [13].

Two studies have investigated the GRFs experienced under the leading limb, but the magnitudes of the GRFs were very different between these studies [7, 40]. MacWilliams et al [7] reported maximal posterior (i.e. braking) and vertical GRFs of 0.72 BW and 1.5 BW, respectively, whereas Guido and Werner [40] reported values of 2.45 BW and 2.02 BW, respectively. Both of these studies investigated collegiate pitchers and used artificial pitching mounds. Differences may have arisen due to individual differences in technique, or different experience levels among the participants. Alternatively, participants in the study conducted by MacWilliams et al [7] may not have performed to their maximal capacity. The position of the force plate in the slope of the pitching mound was adjusted to accommodate for each participant's stride length [7]. However, the vertical GRF was greater than the posterior GRF, which suggests participants may have focused on landing on the force plate rather than producing a maximal effort drive towards the home plate. Additionally, there was a lack of an initial impact transient after foot contact and the GRFs gradually increased until they peaked just prior to ball release [7]. Conversely, the force plate used in the study conducted by Guido and Werner was larger, with dimensions of 0.6 m x 1.2 m [40]. This may have allowed the participants to propel their body forwards with maximal effort without worrying about landing on the force plate. The larger posterior GRF relative to the vertical GRF suggests that these pitchers more effectively drove their body towards the home plate. However, no performance outcomes were reported in either of these studies. Further research is required to better understand these braking GRFs experienced during baseball pitching.

Regardless of the differences seen in the magnitudes of the braking GRFs between studies, the braking forces at foot contact were larger than the propulsive forces [7, 8, 40]. The downward slope of the pitching mound and the propulsive force generated during the stride phase would have contributed to the braking forces. The braking force provides the energy that is transmitted up the body and through to the ball [9]. Therefore, pitchers need to maximise the braking forces generated to increase the amount of energy within the kinetic chain. Upon lead foot contact, the braking force would act to rapidly decelerate the shank of the leading leg [40]. The inertia of the body would then act to maintain the linear movement of the upper body, which may result in knee extension, hip flexion and forward and lateral flexion of the trunk if pitchers maintain a stable shank position. Strong positive correlations have been observed between the linear velocity of the wrist and the propulsive and braking forces generated during the stride phase and after foot contact, respectively [7]. Therefore, producing larger braking forces may enhance ball velocity if energy is transmitted up the kinetic chain appropriately.

A medial GRF was also experienced just after foot contact [40]. This medial GRF acts to decelerate the leading leg as it swings around from the balance position. Consequently, the trunk may experience greater axial rotation, which may be used to accelerate the ball. The initial axial rotation of the pelvis and trunk to open the body towards the home plate further contributes to the medial GRF experienced after foot contact. This medial GRF tended to decrease later in the arm cocking phase, which is presumably due to the continued rotation of the pelvis and trunk [13, 40].

2.1.4. Arm acceleration phase

The arm acceleration phase follows on from the arm cocking phase and continues through to the instant of ball release. The duration of this phase is only 0.03 to 0.05 seconds, which is approximately 2% of the pitching cycle [4, 36]. During this phase, the pelvis and upper torso continue to rotate towards the home plate to transfer energy to the throwing arm. The throwing arm is then used to rapidly accelerate the ball as the arm internally rotates and extends from its cocked position. The maximal elbow extension angular velocity occurs prior to ball release, while maximal internal rotation of the shoulder occurs at ball release, or just after ball release [3, 14, 15, 27, 41]. The actions of the pelvis and torso enhance the angular velocity of elbow extension, by accelerating the upper arm [42]. Forearm pronation occurs approximately 0.01 seconds before ball release and the maximal angular velocity for wrist flexion occurs at approximately the time of ball release to further accelerate the ball [27]. However, the wrist only moves into a neutral position at ball release and does not move into a flexed position [26, 28]. Additional wrist movement may impart spin on the ball or alter the trajectory of the ball after ball release.

During the arm acceleration phase, the posterior and vertical GRFs decreased and a lateral GRF was produced [7, 40]. This lateral GRF increases leading up to ball release and just after ball release, the lateral GRF peaks at a magnitude of 0.45 BW [40]. The continued rotation of the pelvis and trunk in the transverse plane and the movement of the throwing arm presumably produce this lateral GRF [40]. In the study conducted by MacWilliams et al [7], a maximal lateral GRF value of only 0.10 BW was reported, further suggesting the participants in their study may not have performed to their maximal capacity.

2.1.5. Arm deceleration phase and follow through

The arm deceleration and follow through phases are used to control the deceleration of the throwing limb after ball release to prevent injury and to move the body into a balanced fielding position [4, 6]. The arm deceleration phase occurs after ball release and ends at maximal internal rotation of the shoulder. After ball release, the shoulder continues to horizontally adduct and internally rotate, the elbow flexes and the radioulnar joint continues pronating [4]. Studies have demonstrated that the muscles of the upper and lower extremities are highly active throughout the arm deceleration phase to stabilise the joints and decelerate the movements [36, 43-45]. At the elbow, the biceps brachii was active to prevent hyperextension and injury at the joint, while the pectoralis major and latissimus dorsi remained active to continue the internal rotation and horizontal adduction movements about the shoulder. Therefore, the deceleration of the arm after ball release is not purely passive.

The follow through phase follows on from the arm deceleration phase and continues until the trailing leg is planted and the pitcher has moved into a position where they are ready to field. Previous research has often reported the pitching mechanics of the upper extremities during the arm deceleration phase [27, 28]. However, the pitching mechanics throughout the follow through phase have rarely been reported [41]. This is probably due to the high variability of the pitching mechanics during the follow through phase and because actions during this phase do not influence pitching performance.

2.2. The kinetic chain

To accelerate the ball during baseball pitching, a kinetic chain is used to transfer energy throughout the body [6, 10, 46]. Energy generated by each body segment is transferred to the distally adjacent body segment, moving up the body from the lower extremities, to the pelvis, trunk, upper extremities and then ball [6, 39]. To optimise the energy transfer between segments, pitchers must apply the summation of speed principle. This principle states that body segments within a linked system should be recruited in a proximal-to-distal order and that the distal segments should be recruited once the preceding segment achieves its maximal velocity [10]. Initiating movements in a proximal-to-distal order also tends to recruit the larger muscle groups before the smaller muscle groups located about the more distal joints [43]. Recruiting larger muscle groups earlier in the pitch helps to enhance the movements of the distal body segments [46]. Consequently, greater peak angular velocities tend to be generated about the joints that are recruited later in the pitching cycle. This increase in angular velocities is evident in the transverse plane movements, including the pelvis axial rotation, trunk axial rotation and shoulder internal rotation movements. These motions achieve maximal angular velocities of 660 $deg.s^{-1}$, 1170 $deg.s^{-1}$ and 7550 $deg.s^{-1}$ respectively [41]. From the interactions between adjacent body segments, it can be seen that the movements of each body segment throughout the pitching motion are largely dependent on each other. More efficient energy transfer between body segments would presumably result in greater ball velocity. Therefore, the pitching motion requires coordinated and sequential recruitment of all body segments to maximise ball velocity.

2.2.1. Lower extremities

The lower extremities have two main roles during baseball pitching. During the wind-up and stride phases, the main role of the lower extremities is to generate momentum and drive the body towards the home plate. Following foot contact, the leading leg is then used to provide a stable base of support while the upper body accelerates the ball towards the home plate [7, 8, 35, 36, 40]. The role of the leading leg does not appear to change during the arm cocking and arm acceleration phases. Therefore, the pitching cycle has been modified when analysing the lower extremities so that the arm cocking and arm acceleration phases were combined into one phase, call the acceleration or drive phase [35, 36]. Maximal external rotation of the shoulder was excluded from analysis as it is an event specific to the upper extremities. Furthermore, lower extremity kinematic parameters tend to be analysed either at foot contact or ball release, but not at maximal external rotation of the shoulder. Therefore, this modified pitching cycle is more relevant to the lower extremities. Lower extremity parameters that are often analysed include stride length, foot progression and foot position at foot contact, and knee flexion at foot contact and ball release [3, 14, 17-21]. Milewski and colleagues [16] collected normative kinematic data for the hip, knee and ankle of both legs. However, the pitches were thrown from a flat surface and the kinematics were not reported for the stride phase [16]. The stride phase is an essential phase to analyse for the lower extremities due to their role in initiating movement and generating kinetic energy prior to foot contact.

During the wind-up phase, the trailing leg supports the body weight while the leading leg is elevated. Minimal to moderate activity of the lower extremity musculature was observed in both legs throughout this phase suggesting that the muscles are just stabilising the body and holding the leading leg in a ‘cocked’ position [36]. At the balance position, the height of the leading knee may influence the drive towards the home plate as the leg would generate more potential energy the higher it was lifted. After moving into the balance position, the trailing limb slightly flexes to lower the centre of mass, which causes a decrease in the vertical GRF [8]. This is followed by the pitcher producing a propulsive force using the trailing leg to drive the body forwards [7, 8]. The gastrocnemius, vastus medialis and gluteus maximus muscles of the trailing leg exhibited significantly high muscle activity (greater than 68% of the maximal voluntary isometric contraction [MVIC]) throughout the stride phase [36]. These muscles extend the leg to generate the propulsive force used to drive the body towards the home plate. The rectus femoris of the trailing leg was only moderately active throughout the stride phase, which may be due to its secondary role as a hip flexor [36]. After foot contact, the trailing leg musculature exhibited significantly high activity throughout the acceleration phase [36]. This muscle activity may be used to control the movement of the trailing leg after it leaves the ground following lead foot contact.

In the leading leg, the gastrocnemius, rectus femoris and gluteus maximus muscles exhibited high muscle activity (>66% MVIC) and the vastus medialis muscle was moderately active (42%MVIC) during the stride phase [36]. The knee extensors and gluteus maximus muscles would help extend the leg to lengthen the stride length. Conversely, the gastrocnemius may be used to control the amount of knee extension, as it has previously been suggested that the optimal stride length is approximately 80% of the individual’s body height [2, 26]. Longer stride lengths may be undesirable as they have been observed to be more physiologically demanding, which may cause an earlier onset of fatigue [23]. At stride foot contact, large braking forces are experienced by the leading leg, followed by rapid movements of the upper body throughout the acceleration phase. To support the leading leg after foot contact, the hip, knee and ankle musculature exhibited significantly high muscle activity (99-167% MVIC) [36]. These muscles continued to exhibit high activity throughout the rest of the pitching cycle, presumably to help provide a stable base of support for the upper body [36].

Muscular strength of the lower extremities influences the ability to generate kinetic energy and thus ball velocity [47]. Body mass has been positively correlated with ball velocity, which may reflect greater muscle mass to potentially produce greater propulsive forces [48]. Similarly, a correlation of moderate strength has been observed between whole-body muscle volume and ball speed [49]. However, body mass index and percent body fat were not correlated with ball velocity [49]. While a greater total body mass would contribute to generating a larger braking force upon foot contact, it is probably the active muscle mass that has the greatest influence on the drive towards the home plate. Yamada et al [49] assessed correlations between ball velocity and the muscle volumes of different segments of the body, including the upper arm, lower arm, upper leg and lower leg segments of the dominant and non-dominant limbs and the trunk segment. The strongest correlations with ball velocity were seen for the dominant-side upper leg and the non-dominant side lower leg [49]. The dominant upper leg corresponds with the thigh of the trailing leg, which is important for driving the body towards the home plate and generating forward momentum prior to foot contact. Alternatively, the non-dominant lower leg corresponds to the shank of the leading leg, which is used to provide a stable base of support. The correlations with ball velocity were greater for the lower extremity segments than the upper extremity segments or trunk. From these correlations, it may be suggested that the lower extremities are important for generating energy to transmit through to the ball. Pitchers may also need to provide a stable base of support to effectively utilise the trunk to accelerate the ball. Pitchers' performance in 10m sprints and standing long jumps have been used as predictors of the amount of kinetic energy transferred to the ball [47]. Sprints and standing long jumps are power activities and therefore represent the muscular strength and power of the hip and knee extensors and ankle plantarflexors. These muscles would contribute to the ability to produce large propulsive forces and thus powerfully drive the body towards the home plate. Greater muscular strength may also help absorb the impact force experienced upon lead foot contact and prevent the leading leg from collapsing after foot contact.

While no differences between the muscle volumes of the dominant and non-dominant legs were evident in baseball pitchers, some functional differences have been observed [35]. These functional differences may reflect the different roles of the two legs. The hip flexors, knee flexors and ankle dorsiflexors of the leading leg exhibited greater strength than the trailing leg [35]. The leading leg also exhibited a greater active range of motion for hip flexion [35]. These muscles are important for holding the leg in its flexed position at the balance position and may assist with stabilising the leg after foot contact. Additionally, the greater hip flexion range of motion may enable the leg to be lifted higher at the balance position. The ability to lift the leading leg higher may improve the potential to generate greater braking forces, thus improve ball velocity. Conversely, the trailing leg exhibited greater active ranges of motion for ankle plantarflexion, hip internal rotation and hip extension [35]. The increased active range of motion at the hip in the transverse plane may be due to the internal rotation experienced at the balance position while the body rotates away from the home plate. The increased active ranges of ankle plantarflexion and hip extension movements may be related to the extension of the leg used to drive the body forwards. Possessing greater active ranges of motion for these movements may enable the muscles to contribute to the propulsion of the body at the extremes of these ranges of motions. Increased active ranges of movement may therefore be advantageous to pitching as the potential to produce forward momentum may be improved.

Stride length is often analysed with respect to pitching performance, particularly ball velocity. The term ‘stride length’ is somewhat misleading and biomechanically inaccurate in the pitching literature as it actually refers to the step length achieved during the stride phase. However, to prevent confusion and maintain consistency within the pitching literature, the use of the term ‘stride length’ will be continued throughout this thesis. Some differences in stride length have been reported between studies, which may either be due to individual differences or differences in the operational definitions used for stride length. Some studies have defined stride length as the distance between the front edge of the pitching rubber and the ankle joint centre of the leading foot at the instant of foot contact [2, 14, 15, 17]. Wight et al [21] defined stride length as the distance between the ankle joint centre of the trailing leg to a toe marker on the leading foot at foot contact. More recently, studies have measured stride length as the distance between the ankle joint centres of the trailing and leading legs at the instant of foot contact [3, 16, 50]. These definitions provide consistent measurements of stride length within each study but differences in the methodologies limit the ability to compare values between studies. There are also limitations for each of these methods for calculating stride length. Using an external reference point may not accurately reflect the stride length as it does not account for factors such as the position of the trailing foot relative to the pitching rubber. Measuring stride length using toe markers to calculate stride length may also produce different results, as an increased foot progression angle may shorten the stride length measured. Furthermore, calculating stride length as the distance between the two ankle joint centres at the instant of foot contact does not account for the positional movement of the ankle joint centre as the trailing ankle plantarflexes during the stride phase. Plantarflexion of the trailing ankle would result in a shorter stride length. Therefore, it may be more accurate to define stride length as the distance between the ankle joint centre of the trailing foot at the balance position and the ankle joint centre of the leading foot at the instant of foot contact [23]. This method uses anatomical landmarks and the positions of the feet at the beginning and end of the stride.

Regardless of the differences in the operational definitions of stride length, there is a lack of consensus on whether stride length is related to ball velocity. In a study analysing the development of throwing techniques in children under the age of 15 years, 69.3% of the ball velocity variation could be accounted for by stride length [5]. However, it is unclear how influential the stride length is over ball velocity during baseball pitching. In a comparison between American and Korean pitchers, American pitchers used significantly longer stride lengths and pitched with ball velocities that were approximately 3.4 $m.s^{-1}$ faster than Korean pitchers [15]. The American pitchers achieved stride lengths equating to 91% of their height whereas the Korean pitchers achieved stride lengths of 85% of their height. Conversely, in a study conducted by Matsuo et al [14], no significant differences in the relative stride lengths were observed between low velocity pitchers (pitched ball velocity < 34.2 $m.s^{-1}$) and high velocity pitchers (pitched ball velocity > 38.0 $m.s^{-1}$). There were also no significant differences observed in the relative stride length among pitchers of different experience levels, including youth, high school, collegiate, and professional pitchers [17]. These pitchers all achieved stride lengths of approximately 85% of their body height. Other studies have observed that youth and high school pitchers tend to use stride lengths equating to approximately 70% of their body height [3, 16], whereas collegiate and professional pitchers use longer stride lengths of approximately 77-85% of their height [14, 19, 33]. However, differences in the methodologies used between studies may have contributed to these differences in stride length.

When comparing the fastball pitch with breaking or off-speed pitch types, similar observations regarding stride length have been made. As differences in ball velocities are evident between the fastball and breaking or off-speed pitch types [2, 3, 26, 27], comparing the pitching mechanics of the fastball with other pitch types may help identify factors influencing ball velocity. It has previously been observed that a shorter stride length is used for the curveball compared to the fastball, change-up and slider [2, 26]. The shorter stride length during the curveball pitch was observed along with a ball velocity that was 2 – 7 $m.s^{-1}$ slower than the other pitch types [2, 26]. However, the difference in stride length was minimal, with a difference of only 1-2% body height, which was equivalent to approximately a 2 cm difference. Similarly, Dun et al did not observe significant differences in stride length between the fastball, curveball and change-up pitches [3]. These observations suggest that it may not be the stride length that influences ball velocity. Alternatively, it may be the forward momentum produced during the stride phase and the braking forces generated upon foot contact that influences ball velocity.

Greater forward momentum presumably results in greater braking forces, which would generate more energy to transmit up the kinetic chain. Ramsay et al [22] manipulated pitchers' stride lengths to identify whether there were any changes in the momentum of the body in all three planes of motion. When stride length was lengthened by 25%, the momentum of the body in the sagittal, frontal and transverse planes was greater than when the pitchers shortened their stride by 25% [22]. Lengthening the stride length also reduced the proportion of the arm momentum relative to the total body forward momentum. Decreasing the proportion of the momentum of the arm may help reduce the stress experienced by the arm during the acceleration phase [22]. Conversely, when using shorter stride lengths, the pitcher may predispose their throwing arm to greater elbow valgus moments, as suggested by the increased lateral momentum during the arm acceleration phase [22]. As longer stride lengths are more physiologically demanding, the recommended stride length of 80% body height may reflect the optimal balance between generating momentum and energy expenditure.

When comparing high and low velocity pitchers, the magnitudes of the maximal resultant propulsive GRFs produced under the trailing leg were not significantly different [8]. However, differences in the timing of the maximal resultant GRFs were seen between the faster and slower pitchers, which may have contributed to the differences in the ball velocities generated. Low velocity pitchers achieved the maximal resultant propulsive force earlier than the high velocity pitchers and the resultant GRFs quickly diminished at foot contact. Conversely, the resultant propulsive GRFs did not significantly decrease for the high velocity pitchers at foot contact [8]. In fact, the maximal resultant propulsive GRF occurred at foot contact for the high velocity pitchers. These observations suggest that the timing of the initiation of the drive towards the home plate may influence ball velocity to a greater extent than the magnitude of the propulsive forces produced.

As the leading leg experiences braking forces that can exceed 2.00 BW [40], knee flexion at foot contact would be required to help dissipate the impact force. Greater knee flexion at foot contact may indicate that a greater amount of forward momentum was generated [51]. Accordingly, a greater magnitude of maximal knee flexion has been observed during the fastball pitch compared to the change-up pitch, which is a slower pitch type than the fastball [3]. However, a greater maximal knee flexion angular velocity throughout the arm cocking phase and more knee flexion at the instant of ball release have been observed during slower pitches [14, 15, 19, 48]. Conversely, high velocity pitchers are able to produce greater knee extension velocities at the instant of ball release [14]. The ability to produce faster knee extension velocities is presumably influenced by greater forward momentum of the upper body while the shank of the leading leg is rapidly decelerated upon foot contact. At foot contact, the shank is rotated approximately 20 degrees from the vertical axis. As the ankle slightly dorsiflexes during the arm cocking phase, the shank forward rotates to approximately 10 degrees from the vertical [16]. The shank then maintains this orientation throughout the arm acceleration phase, suggesting that knee extension is caused by the upper body rotating over the shank of the leading leg. The ankle musculature would require strength to maintain this upright orientation of the shank, which would explain the strong correlation between ball velocity and the muscle volume of the leading leg shank.

When compared to the curveball and change-up pitches, more knee extension is also experienced at the instant of ball release during the fastball [2, 3], which supports the idea that greater forward momentum is required to achieve faster ball velocities. Younger and less experienced pitchers exhibit greater variability in the sagittal plane knee movements, which may contribute to the slower ball velocities generated compared to pitchers of higher experience levels [14, 17]. Prolonged knee flexion and multiple instances of knee flexion-extension movements suggest that some pitchers experience redundant movements of the body, which may reduce the efficiency of energy transfer between body segments. Therefore, greater knee extension and reduced variability of the leading knee movement after foot contact may help to improve pitching performance [14, 19].

Foot placement and foot progression also influence pitching performance, particularly the transverse plane movements of the pelvis and trunk. Placing the leading foot in an open or closed position may influence the timing of pelvis movement. It has been suggested that the ideal foot position at foot contact is on the imaginary line that bisects the pitching rubber and the home plate [9]. However, placing the foot slightly more towards the first base for a right-handed pitcher (i.e. in a slightly opened position) may be ideal to allow greater rotation of the pelvis [4, 16]. However, if the foot is planted too far towards the first base (for a right-handed pitcher), the pelvis moves into an opened position earlier in the pitch, which may reduce segmental separation. Alternatively, if the foot is placed too far towards the third base (for a right-handed pitcher), then the pelvis has a limited ability to rotate into an opened position [4, 21]. Either of these two foot placements may result in decreased performance outcomes, or may require the upper extremities to make compensatory movements [52]. In adolescent pitchers, foot placement ranged between 32 cm away from the midline towards an opened pelvis position to 37 cm from the midline towards a closed position. Adolescent pitchers also tended to exhibit a slightly internally rotated foot progression angle at foot contact [3, 16, 50]. Possessing an externally rotated foot progression angle for the leading foot at foot contact (foot facing the first base for a right-handed pitcher) opens the pelvis earlier in the pitching motion, which can increase the anterior force at the shoulder and medial force at the elbow [9]. Consequently, an externally rotated foot progression angle may increase the risk of shoulder and elbow injury and is therefore discouraged during pitching.

2.2.2. Pelvis and trunk

The pelvis and trunk transfer the energy generated by the lower extremities to the throwing arm and ball. Pelvis recruitment occurs during the stride phase, which ideally precedes the initiation of trunk rotation [13, 53]. This timing of pelvis and trunk rotation is critical to enable pitchers to achieve segmental separation between the pelvis and trunk segments and therefore optimise the effect of the stretch-shortening cycle (SSC). Hyperextension of the trunk also contributes to the SSC by further lengthening the core musculature and hence a correlation between ball velocity and greater trunk hyperextension has been previously observed [11, 48]. Utilising the SSC to produce more forceful contractions of the core musculature may enhance the angular momentum of the trunk and increase the lag between the trunk and the throwing arm. Therefore, it may be detrimental to pitching performance or the pitching mechanics if the pelvis and trunk movements are not appropriately sequenced [22, 52].

Premature pelvis rotation has resulted in greater external rotation of the shoulder at foot contact and decreased knee extension velocity at ball release [21]. These parameters have previously been associated with decreased ball velocities and may therefore be detrimental to pitching performance [14, 48]. Additional decreases in kinetic parameters at the shoulder were also observed with premature pelvis rotation, suggesting that pitchers decreased the acceleration of the arm and ball when incorrect timing of the pelvis rotation was used [21]. When the trunk was prematurely recruited, pitchers experienced increased magnitudes of maximal shoulder external rotation, maximal shoulder internal rotation, an increased elbow valgus moment and an increased maximal shoulder proximal force, which may increase the risk of upper extremity injuries [52, 54-56]. Additionally, premature trunk rotation may not give the scapula enough time to move into a stabilised position, potentially resulting in a loss of angular momentum in the throwing arm [56]. Therefore, incorrect timing and sequencing of the pelvis and trunk movements may result in an increased risk of injury or decreased momentum transferred between segments, thus decreased ball velocities. Pitchers should ideally maintain a closed pelvis and trunk position throughout the stride phase [8, 13].

The trunk is considered to be the greatest contributor to ball velocity during pitching, as it exhibited the greatest linear and angular momentum compared to the other body segments [39]. Accordingly, pitchers who can generate faster ball velocities produce greater trunk axial rotation velocity, faster linear velocity of the trunk and greater forward trunk flexion at ball release [5, 12-14, 17, 48]. Less experienced pitchers exhibit greater variability in the magnitude of forward trunk flexion, which may contribute to the slower ball velocities generated compared to pitchers within the higher levels of competition [18]. Early initiation of the trunk rotation seen in youth pitchers may further contribute to the slower ball velocities [54, 57]. The trunk generates momentum in the transverse and sagittal planes separately. Trunk rotation in the transverse plane is initiated after maximal angular velocity of the pelvis and achieves maximal angular velocity just prior to the maximal external rotation of the shoulder [39]. This rotation of the trunk helps position the throwing arm in the externally rotated position during the arm cocking phase. Once the pitcher achieves maximal shoulder external rotation, pitchers forward flex the trunk to rapidly accelerate the arm [6, 28, 39]. During the arm acceleration phase, low muscle activity has been observed in the rotator cuff, anterior deltoid and pectoralis major muscles, suggesting that the trunk may be the main contributor to the acceleration of the throwing arm [45, 58]. The angular momentum generated by the pelvis and trunk also enhances the maximal elbow extension velocity that can be achieved. It has previously been demonstrated that the maximum elbow extension velocity achieved was doubled when the whole body contributed to accelerating the ball compared to when the throwing motion was limited to only forearm movement [2, 46, 59]. Furthermore, when throwing was restricted to movement of the forearm only, ball velocity was only a third of that achieved when using the whole body to accelerate the ball. Therefore, core strength is important to enable pitchers to exploit the SSC and produce greater accelerations of the trunk to ultimately maximise the acceleration of the upper extremities and ball [12, 13, 49, 60].

Trunk motion in the frontal plane has also been linked to increased ball velocity. However, increased contralateral trunk tilt also tends to result in greater shoulder internal rotation and elbow varus moments and greater shoulder and elbow proximal forces [14, 54, 60, 61]. Oyama et al [60] suggested that excessive contralateral trunk tilt may be used due to weakness of the core musculature, as this movement can be assisted by gravity, unlike axial trunk rotation. From model simulations, it was predicted that 10 degrees of contralateral trunk tilt with 100 degrees of shoulder abduction was the optimal balance between ball velocity and joint loading, particularly at the elbow [61]. It was also reported that magnitudes of contralateral trunk tilt greater than 10 degrees resulted in increased shoulder abduction and higher peak elbow varus torques. Therefore, excessive contralateral tilt may be injurious and the slight increase in ball velocity probably does not outweigh the risk of injury, particularly due to the high prevalence of elbow injuries seen among pitchers [25, 61].

Contralateral trunk tilt and forward flexion of the trunk have also been implicated in pitching accuracy. Contralateral trunk tilt was suggested to influence the horizontal movement of the ball whereas forward flexion of the trunk was suggested to affect the height of ball release [18, 22, 55]. Due to the rapid movement of the throwing arm, pitchers may not be able to compensate for unfavourable trunk positioning during the arm acceleration phase. Consequently, pitching accuracy may decrease with excessive forward and contralateral trunk tilt.

2.2.3. Upper extremities

The throwing arm is the last link in the kinetic chain that is used to transfer energy to the ball prior to ball release. The timing of maximal wrist flexion and shoulder internal rotation angular velocities occur approximately at the instant of ball release [12, 14, 27]. When high velocity pitchers were compared to low velocity pitchers, the high velocity pitchers achieved the maximal shoulder internal rotation angular velocity closer to the instant of ball release [12, 14]. Achieving the maximal shoulder internal rotation velocity closer to ball release may optimise the transfer of energy to the ball, and therefore increase ball velocity. Professional pitchers produce greater peak internal rotation moments at the shoulder compared to youth pitchers [54]. However, when these values were normalised to body mass, the youth pitchers exhibited a greater relative peak moment [54]. Therefore, professional pitchers may be able to better utilise the kinetic chain to effectively transfer energy to the ball, whereas younger pitchers may rely more heavily on the actions of the throwing arm. Greater segmental separation between the pelvis and trunk may assist in improving energy generation within the trunk, thus reducing the need to produce as large shoulder internal rotation torques during the arm acceleration phase. While the upper extremities have an important role during baseball pitching, the research has suggested that pitchers should not rely on the actions of the throwing arm to accelerate the ball [12, 20, 54, 62]. Throwing predominantly with the arm is often observed in young children who have not yet developed a coordinated throwing technique using the entire body [62]. Additionally, greater torques and forces experienced at the shoulder and elbow may increase the risk of injury among pitchers.

The arm cocking phase is used to move the throwing arm into a position that will optimise the transfer of energy from the lower extremities and trunk through to the ball. This requires stabilisation and positional adjustments of the scapula to improve the congruency of the glenohumeral joint for more effective rotation of the humerus [43]. Increased ball velocities have been observed in pitchers who exhibit greater magnitudes of shoulder external rotation [14, 15, 48]. Greater external rotation of the shoulder increases the potential to generate energy to transfer to the ball [14, 63]. Additionally, greater shoulder external rotation would presumably result in greater lengthening of the shoulder internal rotators to improve the efficacy of the SSC. Pitchers experience up to 180 degrees of shoulder external rotation [4, 14, 15]. This magnitude of shoulder external rotation is in excess of 40 – 60 degrees of normal clinical measures [32]. Consequently, pitchers exhibit a greater range of motion for shoulder external rotation in their throwing arm relative to their non-throwing arm and compared to the throwing arm of positional baseball players [63, 64]. Osseous changes within the glenohumeral joint or increased laxity of the glenohumeral ligaments may be the result of repeated exposures to excessive external rotation, resulting in this increased flexibility [32, 64]. Greater shoulder flexibility was suggested to be a pitching-specific adaptation, as the increased range of motion for shoulder external rotation was only observed while the shoulder was abducted [63]. To achieve such large magnitudes of shoulder external rotation, pitchers use rapid trunk axial rotation to produce a lag in the forearm movement, which forces the shoulder into excessive magnitudes of external rotation [63]. Therefore, greater angular momentum of the trunk may increase the external rotation of the shoulder.

Movement at the distal aspect of the throwing arm has also been linked to ball velocity. After foot contact, the elbow flexes as the shoulder begins to abduct [6, 8]. Increased ball velocities have been observed when pitchers experienced more elbow flexion at foot contact [48]. Elbow flexion acts to shorten the length of the arm, which would improve arm mobility and enable faster movement of the arm to move it into its cocked position. This may improve pitching performance as it has previously been observed that ball velocity is negatively correlated with the time it takes to achieve maximal external rotation of the shoulder [48]. This may be due to a faster rate of muscle lengthening brought about by faster external rotation of the shoulder, thus stimulating the stretch receptors to enhance the muscular contraction of the shoulder internal rotators [65]. In comparisons between pitch types, more elbow extension at the instant of ball release has been observed during the fastball compared to the curveball and change-up pitches [2, 3]. Additionally, high velocity pitchers tend to achieve maximal elbow extension velocity earlier in the pitching cycle than low velocity pitchers [14]. These observations suggest that pitchers should quickly extend their elbow during the arm acceleration phase to achieve faster ball velocities. Lengthening the arm during the arm acceleration phase would increase the tangential velocity of the ball, which would contribute to increasing ball velocity. Similarly, pitchers who have longer arms have been observed to achieve faster ball velocities [14, 15].

Wrist flexion also contributes to the acceleration the ball, which requires hyperextension of the wrist during the arm cocking phase [3, 28]. During the fastball pitch, the wrist experiences more hyperextension compared to the curveball [3]. Greater wrist extension increases the potential to generate and transfer energy to the ball. However, a smaller wrist flexion torque is experienced during the fastball compared to the curveball during the acceleration phase [3]. More wrist flexion may be used to apply spin on the ball.

2.2.4. Timing and sequencing of movements

Timing and sequencing of movements are possibly as important as the kinematics and kinetics used during baseball pitching. The lag created between segments enables the muscles to produce more powerful muscular contractions by utilising the SSC [11, 32]. This may enhance the efficiency of the transfer of energy between segments as the muscles are preloaded prior to muscular contractions. Specifically, the abdominal muscles may benefit from the lag of the upper torso rotation relative to the pelvis rotation, while the internal rotators of the shoulder may benefit from the lag of the upper arm movement relative to the upper torso movement. As the trunk rapidly rotates towards the home plate in the transverse plane, a lag in the upper arm motion is induced, which initiates horizontal abduction of the shoulder. As the upper arm is moved into horizontal abduction, the lag produced between the upper arm and forearm forces the shoulder into external rotation [3, 15, 32, 43]. Therefore, incorrect sequencing of these movements may limit the ability to use the SSC as the muscles may not experience the same magnitude of acute lengthening. Greater segmental separation between the pelvis and trunk may enhance the effect of the SSC and reduce the reliance on the upper extremities to accelerate the ball [17, 54]. However, prolonged delays in the recruitment of body segments result in decreased kinetic parameters, which may be detrimental to pitching performance [11]. Therefore, pitchers must time the recruitment of body segments appropriately so that the SSC may be exploited while minimising the amount of elastic energy that is dissipated as heat energy. More efficient use of the kinetic chain to generate and transmit energy throughout the body may help improve pitching performance and decrease the risk of injury.

2.3. Fatigue

Pitchers exhibit a decrease in ball velocity with fatigue or extended play [20, 24]. To maintain performance throughout a game, the effect fatigue has on the pitching mechanics needs to be understood. However, the effect of fatigue during baseball pitching has not been thoroughly investigated [20, 24, 66]. These studies have primarily focused on the upper extremities, pelvis and torso. Murray et al observed a decreased magnitude of maximal shoulder external rotation, decreased distraction forces at the shoulder and elbow and a decreased shoulder horizontal adduction torque with fatigue [24]. These changes in the upper extremity pitching mechanics would decrease the potential to generate kinetic energy. Additionally, as the distraction forces at the shoulder and elbow were smaller, it may be inferred that the acceleration of the throwing arm was also reduced, which would negatively affect ball velocity. A less extended leading knee at ball release was also observed when the pitchers were fatigued [24]. Decreased lead knee extension at ball release may indicate that pitchers produced less forward momentum. However, using more knee flexion may be a protective mechanism to help stabilise the knee when pitchers begin to experience fatigue. Escamilla and colleagues did not observe kinematic differences in the upper and lower extremities [20]. They did report that pitchers exhibited a more upright trunk at ball release with fatigue, which suggests that the pitchers generated less forward momentum of the upper body. This change in the trunk position was suggested to be caused by the fatigue of the knee extensors, as the knee extensors stabilise the leg to enable trunk rotation. However, these two studies did not complete pre- and post-tests to assess the pitchers' muscular strength.

Muscular fatigue often results in a reduced ability to produce powerful concentric contractions and absorb energy using eccentric muscular contractions [67-69]. This has been demonstrated in the lower extremities by a decreased jump height and altered landing kinematics during jumping tasks after the completion of a fatigue protocol [67, 68]. Therefore, changes in joint kinematics may be indicative of muscular fatigue. Similar kinematic responses to fatigue may also be experienced during baseball pitching; however, this needs to be further investigated. One study has assessed muscular strength of the scapular stabilisers and the shoulder and hip musculature in collegiate and Minor League baseball pitchers before and after a baseball game [66]. Strength deficits were only observed in the shoulder musculature of the throwing arm, including the shoulder flexors, abductors, adductors and internal rotators [66]. Due to the rapid rotation and distraction forces experienced at the shoulder, large compressive forces may be required to stabilise the glenohumeral joint [30, 32]. Therefore, it is not surprising that the shoulder musculature experienced fatigue after the game. However, these strength tests were completed 15 - 25 minutes after the pitcher finished pitching during the game. During this period, the scapula stabilisers and hip musculature may have had time to recover. Therefore, it remains unknown whether the hip musculature experienced fatigue while pitching in a live game. Additionally, the knee and ankle musculature were not assessed for muscular fatigue. Further research regarding fatigue and/or extended play during baseball is required, particularly pertaining to the lower extremities as they are the first contributors to the generation of linear and angular momentum.

2.4. Summary

The literature pertaining to baseball pitching has highlighted the highly interactive nature of the pitching motion. The actions of the lower extremities influence the actions of the pelvis and trunk, which influence the actions of the upper extremities. When pitchers use the optimal timing and sequencing of movements, faster ball velocities may be achieved with smaller relative torques and forces in the upper extremities. Experienced pitchers tend to utilise pitching mechanics that promote greater efficiency in the transfer of energy between body segments to achieve faster ball velocities. Faster ball velocities may also be attributed to greater consistency of pitching mechanics. However, youth and high school pitchers exhibit greater variability in their pitching mechanics. Specifically, less experienced pitchers exhibited increased variability in the lead foot placement at foot contact, knee flexion at foot contact, the magnitude of maximal shoulder external rotation and the magnitude of forward trunk tilt at ball release [18]. These parameters have all been suggested to influence ball velocity. Therefore, improving the consistency of the pitching mechanics may help to improve pitching performance in youth and high school pitchers.

Pitching mechanics tend to be altered with the onset of fatigue, which may contribute to the increased risk of injury associated with increased pitch counts [25]. Altered pitching mechanics may also contribute to the decreased ball velocity often observed with fatigue. Early changes in the pitching mechanics may contribute to the changes made later in the pitching cycle, particularly the changes that affect the production of momentum. Therefore, it is important to identify and correct these changes in the pitching mechanics to maintain pitching performance throughout a game. Reduced momentum generated in the early phases of the pitching cycle may result in decreased energy transferred to the trunk, upper extremities and ball. However, the analysis of baseball pitching has often excluded the pitching mechanics throughout the wind-up and stride phases. This information would complement the limited research regarding the lower extremities and their contribution to ball velocity.

Therefore, more research is required to further understand the contribution of the lower extremities during baseball pitching and the effects that fatigue may have on pitching performance.

3. Methods

3.1. Participants

Twelve male adolescent pitchers (age: 14.9 ± 0.7 years, height: 1.74 ± 0.07 m, mass: 72.8 ± 13.5 kg) participated in this study. Participants were recruited through the Hospital for Special Surgery's Sport Medicine and Shoulder Service, team personnel and by public advertisements. To be eligible for recruitment, athletes must have pitched within the previous month, but not within the five days prior to testing. Participants were excluded if they were diagnosed with shoulder pain or dysfunction by a physical therapist prior to testing, had a previous history of injury or surgery to the shoulder of the throwing arm, or had a glenohumeral internal rotation deficit of more than 25 degrees from side to side [70]. Nine of the participants were right-hand dominant and three were left-hand dominant. Participants had an average of 5.2 ± 2.1 years of pitching experience, with a range of two to eight years of experience. Participants and their parents provided informed written assent and consent, respectively. The study was approved by the Hospital for Special Surgery Institutional Review Board.

3.2. Marker placement

Participants wore shorts and their own shoes. Retro-reflective markers were attached to the body at specific bony landmarks of the trunk, upper extremities and lower extremities (Fig. 3.1). On the trunk, single markers were affixed over the acromioclavicular joint of the non-throwing shoulder, proximal and distal ends of the sternum, C7 spinous process, T8 spinous process, the sacrum, the left posterior superior iliac spine and bilaterally on the anterior superior iliac spine. Rigid clusters of four markers were attached to the throwing arm, with specific locations on the lateral aspect of the scapula spine [71], the proximal end of the ulna inferior to the olecranon process, and the distal end of the posterior forearm. A rigid cluster of three markers was also attached to the posterior surface of the throwing hand. Individual markers were attached bilaterally to the greater trochanter, medial and lateral femoral epicondyles and malleoli and the tibial tuberosity. Markers were attached to the outer surface of the shoe over the bases of the first and fifth metatarsals, at the distal end of the second toe and four markers were attached to the posterior surface of the heel of the shoe. Rigid clusters of four markers were attached bilaterally to the lateral side of the thigh and shank. The rigid clusters were secured using self-adhesive bandages to reduce movement artefact. The markers on the medial and lateral femoral condyles and malleoli, greater trochanter, tibial tuberosity and second toe of both legs were only used during calibration and were removed prior to the pitching trials. Reflective tape was also fixed to the sides of the baseballs to help identify when ball release occurred.

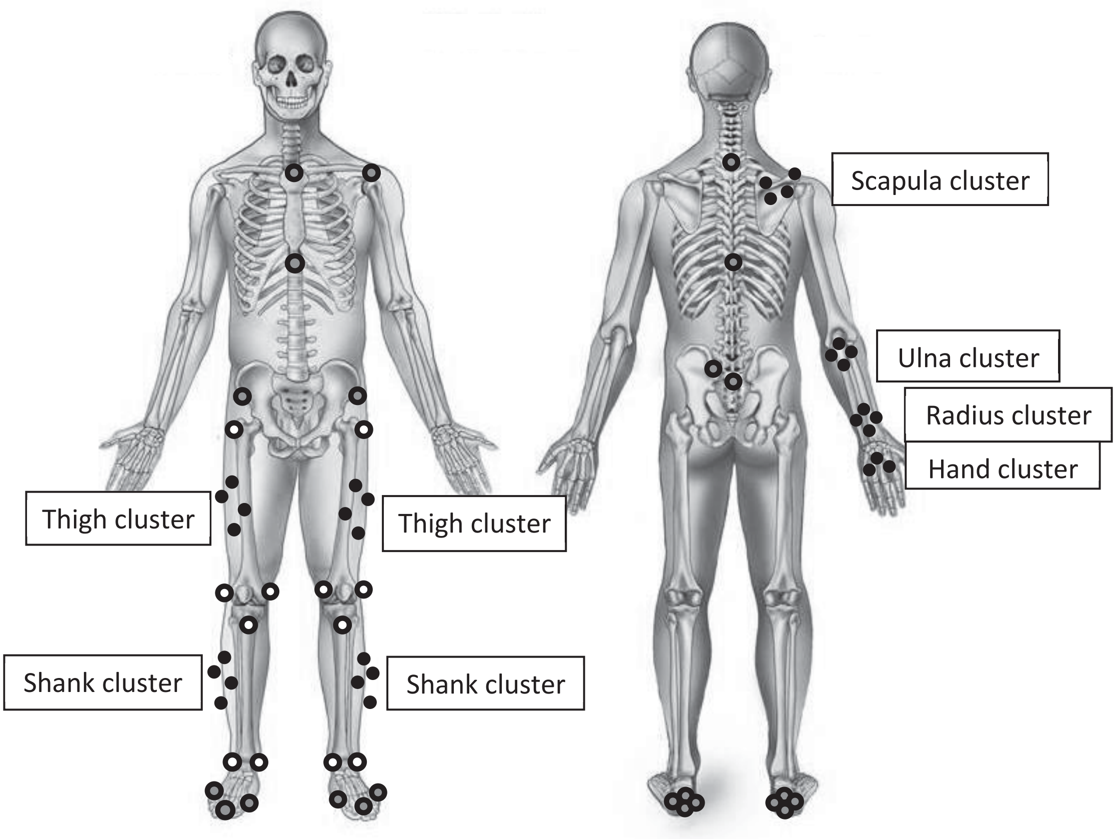

Fig. 3.1. Anterior and posterior view of the marker set for a right-handed pitcher (scapula, ulna, radius and hand clusters on the left arm for left-handed pitchers). Solid black circles identify rigid clusters of markers, grey circles identify single markers and white circles identify the single markers used only for calibration.

3.3. Data collection

A 12-camera (Eagle-4; Motion Analysis; CA) optical motion capture system (Cortex; Motion Analysis Corporation; Santa Rosa; CA) was used to collect 3D kinematics at a sampling rate of 250 Hz. Prior to marker calibration, participants completed a self-selected warm up including stretches followed by ten warm up pitches while wearing the full marker set [16]. A static trial was then collected to calibrate the marker set. During the static trial, participants stood upright, looking straight ahead, with a neutral pelvis orientation, arms abducted to 45 degrees and their feet were shoulder-width apart and facing forwards. Additional functional trials were also collected as part of the calibration to determine the joint coordinate systems and joint centres for the glenohumeral joint, elbow, forearm and wrist. As the main focus of the present study was the lower extremities, the functional calibration trials for the upper extremity joints will not be described. The hip joint centres were identified using a previously developed regression definition [72]. The knee and ankle joint centres were identified as the midpoint between the medial and lateral femoral epicondyles and malleoli, respectively.

Participants completed six sets of 15 fastball pitches (i.e. 90 pitches) with five minute rest periods between sets. In a previous study, 15 pitches were considered to be the typical pitch count for an inning [20]. The total pitch count used in the present study complied with the 2010 Little League Baseball Regulations for this age group [57] and was used to simulate a full game to investigate the effects of upper extremity fatigue during baseball pitching. Participants pitched from a 10 inch tall artificial pitching mound towards a pitching net, placed at the regulation distance of 60 feet and 6 inches. Ball velocity was obtained using a radar gun (Sports Radar DT200, Sports Radar Ltd, Homosassa, FL), which was placed near the pitching net. Ball velocity was corrected as the radar gun was not placed in line with the trajectory of the ball. The corrected ball velocity was calculated as the raw speed divided by the cosine of the angle of the speed gun relative to the desired trajectory of the ball. Pitching accuracy was identified by a designated strike zone configured on the pitching net. If the pitch hit the net within the strike zone, the pitch was categorised as a 'Strike'. Inaccurate pitches, or 'ball' pitches, were split into two subcategories (i.e. ‘Ball 1’ and ‘Ball 2’). A Ball 1 was defined as a pitch thrown, whereby the ball hit the area of the net around the strike zone or if the ball hit the frame of the pitching net. A Ball 2 was operationally defined as a pitch thrown that missed the pitching net completely. The number of Strike, Ball 1 and Ball 2 pitches within the baseline and final sets were expressed as percentage values within each respective set of 15 pitches.

3.4. Data processing and analysis

Data were processed using Cortex (Motion Analysis Corp; Santa Rosa; CA). Preliminary analyses on ball velocity concluded that optimal pitching performance occurred in the second set rather than the first set (unpublished). Therefore, the last five pitches of the second set were analysed to represent the baseline performance and the last five pitches of the sixth set were analysed to assess the end of game performance. One participant only completed five sets due to shoulder pain, so the last five pitches of the fifth set was analysed for this participant. When markers were unavailable or missing, the marker positions were interpolated using the relative positions of other markers on the same segment, while assuming rigid bodies for the lower extremity segments. Pitching trials were excluded from analysis if markers that were missing could not be interpolated. Earlier pitching trials from the same set were used for analysis if pitching trials from the last five of the set were excluded to ensure five pitches of each set were analysed.

Data were analysed in Visual3D (C-Motion Inc; Germantown; MD). Data were filtered using fourth-order low-pass Butterworth filters with cut-off frequencies of 20 Hz for the upper extremity and trunk marker positions and 12 Hz for the lower extremity and pelvis marker positions. Separate cut-off frequencies were necessary due to different segment velocities during baseball pitching. The modified pitching cycle in this study was identified as the balance position (0% pitch cycle) through maximal internal rotation of the shoulder (100% of the pitch cycle). The balance position and stride phase were included in the analysis of the pitching mechanics due to the importance of the lower extremities to initiate the drive of the body towards the home plate [8, 36]. Phases of the pitching cycle were defined with events as outlined in previous research, including the stride phase (balance position to foot contact), acceleration phase (foot contact to ball release), and deceleration phase (ball release to maximum shoulder internal rotation) [35, 36]. The balance position was identified when the knee reached its highest position [6]. Foot contact was identified when the velocity of the lead foot fell below 0.5 m.s^{-1}. When ball markers were available, ball release was visually identified as the first frame where the ball had left the hand. If the ball markers were not available, replicated linear positions of the forearm and hand segments from those found in a previously analysed trial were used as surrogate markers of release.

Several kinematic parameters were analysed within the global coordinate system. Stride length was calculated as the vector between the ankle joint centres of the trailing limb at the balance position and the leading limb at foot contact [23]. For comparisons between individuals, stride length was normalised to body height (% height). Foot progression was calculated as the angle between the long axis of the foot relative to the global y-direction, i.e. the direction of the pitching net. If the foot was facing the pitching net, the foot progression angle was 0 degrees. If the foot was internally rotated, the progression angle was a positive value and if the foot was externally rotated, the foot progression angle was a negative value. Foot progression was calculated for both feet at the balance position and for the leading foot at foot contact and at ball release.

Angular displacements (deg) and angular velocities (deg.s^{-1}) were calculated for the hip, knee and ankle of the trailing and leading legs throughout the pitching cycle. Maximal angular displacements were calculated at the hip (sagittal, frontal, transverse planes), knee (sagittal plane) and ankle (sagittal plane) throughout the stride phase for the leading and trailing legs. Angular displacements of the hip, knee and ankle for the leading and trailing limbs were also calculated at the balance position, foot contact and at ball release. Maximal angular velocities were calculated for the hip (sagittal, frontal, transverse planes), knee (sagittal plane) and ankle (sagittal plane) of the trailing limb during the stride phase. The maximal knee extension angular velocity in the leading leg during the acceleration phase was also calculated. Angular velocities of the hip (sagittal, frontal, transverse planes), knee (sagittal plane) and ankle (sagittal plane) for the leading and trailing limbs at foot contact and ball release were also calculated.

The duration of the pitching cycle was defined as the time between the balance position and maximal shoulder internal rotation (sec). The normalised time of foot contact and ball release were also calculated and expressed as a percentage of the pitching cycle duration (% pitching cycle). The normalised time that maximal angular displacements and maximal angular velocities occurred within the stride phase were calculated and expressed as a percentage of the stride phase duration (% stride phase).

3.5. Statistical analysis

Paired T-tests were completed to compare kinematic and temporal parameters and performance outcomes between the baseline and final sets (SPSS Statistics v22; IBM Corp; Armonk; NY). The kinematic parameters included stride length and the angular displacement and angular velocity parameters previously described. Temporal parameters included pitch duration, relative timing of events, relative timing of maximal angular displacements and relative timing of maximal angular velocities. The performance outcomes that were analysed included average ball speed and the percentages of Strike, Ball 1 and Ball 2 pitches. Significance was set at $p < 0.05$.

Intra-class correlation coefficients (ICCs) were calculated in SPSS to assess the variability of the angular displacements at the hip (sagittal, frontal and transverse planes), knee (sagittal plane) and ankle (sagittal plane) and foot progression at the balance position.

4. Results

For the primary outcome of the study, statistically significant differences were observed in the kinematic (Tables 4.1, 4.2 and 4.3) and temporal (Table 4.4) parameters between the baseline and final sets.

4.1. Displacements

4.1.1. Maximal angular displacements

No significant differences were observed throughout the stride phase for any maximal angular displacements of the leading leg between the baseline and final sets. However, there was a trend towards a significantly decreased maximal hip flexion of the leading hip throughout the stride in the final set ($p = 0.083$) (Fig. 4.1). In the final set, the trailing limb experienced decreased maximal hip flexion and extension ($p = 0.025$ and $p = 0.04$, respectively), increased maximal hip internal rotation ($p = 0.003$), decreased maximal knee extension ($p = 0.026$), and decreased maximal ankle plantarflexion ($p = 0.017$) (Fig. 4.2). There was also a trend for increased maximal ankle dorsiflexion of the trailing leg in the final set compared to the baseline set ($p = 0.075$).

4.1.2. Displacements at events

At the balance position, there were no significant differences in the angular displacements at the hip, knee or ankle of the leading leg between the baseline and final sets. However, in the final set there was a trend towards decreased hip flexion of the leading leg at the balance position ($p = 0.082$). The trailing hip experienced more internal rotation at the balance position in the final set ($p = 0.042$) and was positioned in an internally rotated position, whereas the trailing hip experienced greater external rotation in the baseline set (Fig. 4.2). On average, the trailing knee experienced 3 degrees more flexion in the final set compared to the baseline set ($p = 0.003$). There were also trends towards significantly increased hip flexion ($p = 0.064$) and decreased foot external rotation ($p = 0.054$) of the trailing leg during the final set.

In the final set, the leading hip was less flexed ($p = 0.022$) and more abducted ($p = 0.024$) at foot contact compared to the baseline set (Fig. 4.1). No other significant differences were observed in the leading leg at foot contact between the baseline and final sets. The trailing ankle was less plantarflexed at foot contact in the final set ($p = 0.014$). No significant differences in the leading leg angular displacements were observed at ball release between the baseline and final sets. No significant differences in stride length were observed between the baseline and final sets ($p = 0.118$).

4.2. Angular velocities

4.2.1. Maximal angular velocities

During the stride phase, the maximal hip abduction and knee extension velocities decreased by 13.1 deg.s^{-1} ($p = 0.050$) and 23.2 deg.s^{-1} ($p = 0.011$), respectively, in the final set. No other significant differences in the maximal angular velocities throughout the stride phase were observed between the baseline and final sets. During the acceleration phase, there was no significant difference in the maximal knee extension angular velocity of the leading leg.

4.2.2. Angular velocities at events

There were no significant differences in the angular velocities at the hip, knee or ankle of the leading leg at foot contact. There was almost twice the plantarflexion velocity of the trailing ankle at foot contact in the final set compared to baseline ($p = 0.042$). No other differences in angular velocities were observed at foot contact. There were no significant differences in the angular velocities for the leading or trailing limbs at ball release. However, there was a trend towards a significant decrease in the hip flexion angular velocity of the trailing leg at ball release ($p = 0.074$).

4.3. Temporal parameters

There were no statistically significant differences in the duration of the pitching cycle and the relative timing of when ball release occurred between the two sets. However, there was a trend for foot contact to occur earlier in the pitches of the final set compared to the baseline set. This difference was very small, with foot contact occurring approximately 1.2% of the pitching cycle earlier in the final set ($p = 0.078$).

For the leading limb, the maximal hip abduction displacement occurred almost 2% of the stride phase later in the final set compared to the baseline set ($p = 0.013$). No other differences in the timing of the maximal angular displacements were observed for the leading limb. For the trailing limb, no significant differences were observed for the timing of maximal angular displacements during the stride phase. There was a trend towards maximal hip internal rotation occurring earlier in the stride phase in the final set ($p = 0.080$).

Maximal hip extension angular velocity for the trailing limb during stride occurred 1.5% of the stride phase later in the final set than during the baseline set ($p = 0.012$). No other differences in angular velocities were seen at the hip or knee. At the ankle of the trailing limb, there was a trend towards the maximal ankle plantarflexion angular velocity occurring slightly later in the final set ($p = 0.064$).

4.4. Performance outcomes

For the secondary outcome of the study, statistically significant differences in the pitching performance outcomes were observed in the final set of the simulated game compared to the baseline performance (Table 4.5). In the final set, ball velocity decreased by 1.2 $m.s^{-1}$ compared to the baseline set ($p = 0.001$). There was a trend for an increased percentage of Ball 2 pitches in the final set (p = 0.053). However, there were no statistically significant differences in the percentages of Strike or Ball 1 pitches.

4.5. Variability of the angular displacements at the balance position

Very little differences in the variability of the angular displacements at the balance position were observed, as indicated by similar ICC values between the baseline and final sets (Table 4.6). The ICC values were also quite high for the angular displacements of both legs at the balance position, with all ICC values greater than 0.700, suggesting low variability of the angular displacements at the balance position for both legs within each set.

Table 4.1. Comparison of the mean ± SD maximal angular displacements (deg) during the stride phase in the baseline and final sets.

	Baseline Set	Final Set	P Value	Δ
Leading Limb				
Hip Flexion	91.7 ± 10.2	88.4 ± 11.2	*0.083*	-3.6
Hip Extension	42.6 ± 13.4	41.9 ± 12.5	0.688	
Hip Adduction	5.3 ± 10.5	5.6 ± 10.7	0.727	
Hip Abduction	38.3 ± 7.3	38.8 ± 8.0	0.556	
Hip Internal Rotation	2.0 ± 7.3	2.0 ± 7.7	0.924	
Hip External Rotation	26.3 ± 10.4	26.5 ± 11.0	0.874	
Knee Flexion	101.5 ± 11.8	100.6 ± 12.7	0.521	
Knee Extension	-18.9 ± 20.1	-18.1 ± 18.5	0.565	
Ankle Dorsiflexion	7.8 ± 7.8	8.6 ± 7.1	0.347	
Ankle Plantarflexion	20.7 ± 6.4	19.6 ± 7.1	0.278	
Trailing Limb				
Hip Flexion	49.4 ± 10.8	46.8 ± 10.5	**0.025**	-5.3
Hip Extension	14.7 ± 9.8	11.6 ± 10.3	**0.024**	-21.1
Hip Adduction	-10.8 ± 4.7	-9.8 ± 4.9	0.163	
Hip Abduction	40.8 ± 8.8	40.3 ± 9.7	0.708	
Hip Internal Rotation	4.6 ± 7.5	7.4 ± 6.3	**0.003**	60.9
Hip External Rotation	16.6 ± 10.7	15.0 ± 9.1	0.129	
Knee Flexion	61.8 ± 7.8	61.9 ± 8.0	0.860	
Knee Extension	-21.7 ± 8.1	-23.5 ± 7.9	**0.026**	8.3
Ankle Dorsiflexion	23.9 ± 8.0	25.2 ± 8.5	*0.075*	5.4
Ankle Plantarflexion	30.2 ± 14.5	24.2 ± 15.3	**0.017**	-19.9

Note: Bold text identifies significant differences ($p < 0.05$). Italicised text identifies trends toward statistical significance ($p < 0.10$). Negative angular displacement values indicate that the joint remained in the opposite joint orientation (e.g. negative knee extension values indicate that the knee remained in a flexed orientation). Δ is the percent (%) change relative to the baseline set, where positive values indicate increased angular displacement whereas negative values indicate decreased angular displacement.

Table 4.2. Comparison of mean ± SD displacements at events between the baseline and final sets.

	Baseline Set	Final Set	P Value	Δ
Angular Displacements at the Balance Position (deg)				
Leading Leg				
Hip Flexion	90.6 ± 11.1	87.1 ± 12.2	*0.082*	-3.9
Hip Abduction	2.9 ± 13.9	1.0 ± 13.0	0.116	
Hip External Rotation	12.9 ± 5.6	11.8 ± 5.8	0.161	
Knee Flexion	98.9 ± 12.0	98.0 ± 13.0	0.546	
Ankle Plantarflexion	2.9 ± 13.2	1.3 ± 11.3	0.115	
Ankle Eversion	3.0 ± 6.8	2.8 ± 7.6	0.815	
Foot Adduction	8.5 ± 9.6	7.7 ± 8.5	0.300	
Foot Progression	123.7 ± 17.2	123.4 ± 17.2	0.911	
Trailing Leg				
Hip Flexion	4.7 ± 11.0	7.3 ± 11.0	*0.064*	55.3
Hip Abduction	-13.9 ± 7.3	-12.9 ± 6.7	0.246	
Hip Int./Ext. Rotation	-1.9 ± 9.9	1.4 ± 7.3	**0.042**	-173.7
Knee Flexion	22.5 ± 8.2	25.5 ± 10.1	**0.003**	13.3
Ankle Dorsiflexion	10.4 ± 4.8	11.2 ± 5.0	0.239	
Ankle Inversion/Eversion	1.8 ± 8.0	-0.6 ± 8.0	0.167	
Foot Adduction	17.2 ± 7.7	17.8 ± 8.7	0.626	
Foot Progression	-105.7 ± 11.1	-102.7 ± 10.6	*0.054*	-2.8
Angular Displacements at Foot Contact (deg)				
Leading Leg				
Hip Flexion	69.5 ± 10.1	66.5 ± 11.8	**0.022**	-4.3
Hip Abduction	20.7 ± 8.9	25.4 ± 6.0	**0.024**	22.7
Hip External Rotation	18.3 ± 14.7	19.1 ± 14.2	0.710	
Knee Flexion	41.7 ± 8.9	40.8 ± 9.5	0.346	
Ankle Plantarflexion	13.6 ± 7.4	14.1 ± 8.4	0.611	
Foot Progression	6.3 ± 16.2	7.3 ± 15.2	0.497	
Trailing Leg				
Ankle Plantarflexion	30.1 ± 14.7	23.8 ± 16.2	**0.014**	-20.9
Angular Displacements at Ball Release (deg)				
Leading Leg				
Hip Flexion	80.4 ± 10.4	79.1 ± 10.9	0.244	
Hip Adduction	18.1 ± 8.0	17.3 ± 10.0	0.359	
Hip External Rotation	7.1 ± 11.0	5.8 ± 9.8	0.383	
Knee Flexion	31.8 ± 11.2	31.7 ± 11.5	0.912	
Ankle Plantarflexion	14.7 ± 9.8	13.8 ± 9.9	0.214	
Foot Progression	3.7 ± 13.7	3.7 ± 12.5	0.940	
Stride Length (% height)	77.3 ± 6.4	76.6 ± 6.2	0.201	

Note: Bold text identifies significant differences ($p < 0.05$). Italicised text identifies trends toward statistical significance ($p < 0.10$). Δ is the percent (%) change relative to the baseline set.

Table 4.3. Comparison of mean ± SD angular velocities (deg. s^{-1}) between the baseline and final sets.

	Baseline Set	Final Set	P Value	Δ
Maximal Angular Velocities				
Trailing Limb during Stride Phase				
Hip Extension	107.2 ± 24.2	105.6 ± 36.5	0.853	
Hip Abduction	116.7 ± 36.6	103.6 ± 28.8	**0.050**	-11.2
Hip External Rotation	233.1 ± 60.5	220.2 ± 56.4	0.595	
Knee Extension	144.9 ± 63.3	121.7 ± 62.0	**0.011**	-16.0
Ankle Plantarflexion	436.6 ± 161.6	395.0 ± 160.5	0.199	
Leading Limb during Acceleration Phase				
Knee Extension	177.1 ± 105.9	173.3 ± 96.7	0.742	
Angular Velocities at Foot Contact				
Leading Limb				
Hip Flexion	96.9 ± 123.0	85.8 ± 128.4	0.550	
Hip Adduction	308.0 ± 88.6	330.6 ± 79.8	0.177	
Hip External Rotation	298.9 ± 119.6	270.7 ± 128.7	0.135	
Knee Flexion	31.4 ± 73.0	48.4 ± 65.5	0.247	
Ankle Plantarflexion	22.7 ± 101.7	13.5 ± 81.9	0.507	
Trailing Limb				
Hip Flexion	84.3 ± 49.9	83.2 ± 80.6	0.935	
Hip Adduction	206.9 ± 161.5	242.6 ± 152.9	0.290	
Hip External Rotation	185.3 ± 67.4	174.7 ± 52.4	0.687	
Knee Extension	88.7 ± 87.6	78.7 ± 77.7	0.410	
Ankle Plantarflexion	117.7 ± 121.9	219.2 ± 153.9	**0.042**	86.2
Angular Velocities at Ball Release				
Leading Limb				
Hip Extension	70.2 ± 103.2	74.9 ± 110.5	0.706	
Hip Adduction	38.6 ± 94.4	34.2 ± 113.3	0.803	
Hip External Rotation	93.0 ± 114.0	109.2 ± 119.8	0.400	
Knee Extension	124.7 ± 125.6	113.8 ± 125.9	0.380	
Ankle Dorsiflexion	1.5 ± 58.0	3.9 ± 60.3	0.723	
Trailing Limb				
Hip Flexion	205.0 ± 82.5	175.2 ± 80.7	*0.074*	-14.5
Hip Adduction	43.9 ± 80.2	35.4 ± 104.2	0.632	
Hip External Rotation	10.6 ± 109.9	7.2 ± 124.8	0.828	
Knee Flexion	131.6 ± 114.8	114.8 ± 103.9	0.540	
Ankle Dorsiflexion	35.0 ± 98.5	53.3 ± 73.1	0.256	

Note: Bold text identifies significant differences ($p < 0.05$). Italicised text identifies trends toward statistical significance ($p < 0.10$). Δ is the percent (%) change relative to the baseline set.

Table 4.4. Comparison of mean ± SD values for temporal parameters between the baseline and final sets.

	Baseline Set	Final Set	P Value	Δ
Temporal parameters				
Pitch Duration (sec)	1.30 ± 0.16	1.31 ± 0.12	0.858	
Time of Foot Contact (% Pitching cycle)	67.2 ± 3.5	66.0 ± 3.1	*0.078*	-1.8
Time of Ball Release (% Pitching cycle)	77.8 ± 2.7	77.8 ± 2.2	0.829	
Timing of Maximal Angular Displacements during Stride phase (% Stride phase)				
Leading Limb				
Hip Extension	81.9 ± 8.3	83.2 ± 7.3	0.144	
Hip Abduction	88.9 ± 3.1	90.6 ± 2.7	**0.013**	1.9
Hip Internal Rotation	71.9 ± 36.3	78.5 ± 29.0	0.372	
Knee Extension	92.2 ± 4.6	93.3 ± 4.1	0.530	
Trailing Limb				
Hip Flexion	66.5 ± 5.6	67.6 ± 6.6	0.207	
Hip Adduction	24.6 ± 19.1	24.4 ± 15.2	0.969	
Hip Internal Rotation	55.7 ± 29.9	42.3 ± 30.8	*0.080*	-24.1
Knee Flexion	70.2 ± 1.8	70.6 ± 3.4	0.588	
Ankle Dorsiflexion	64.4 ± 8.0	66.1 ± 8.4	0.290	
Timing of Maximal Angular Velocities during Stride phase (% Stride phase)				
Trailing Limb				
Hip Extension	90.9 ± 2.6	92.4 ± 3.05	**0.012**	1.7
Hip Abduction	71.0 ± 10.7	72.8 ± 11.7	0.253	
Hip External Rotation	90.8 ± 9.5	90.8 ± 5.4	0.997	
Knee Extension	92.2 ± 4.6	93.3 ± 4.1	0.190	
Ankle Plantarflexion	96.5 ± 1.5	97.6 ± 1.9	*0.064*	1.1

Note: Bold text identifies significant difference ($p < 0.05$). Italicised text identifies trends toward statistical significance ($p < 0.10$). Pitch duration is calculated as the time from the balance position through to maximum shoulder internal rotation. Δ is the percent (%) change relative to the baseline set.

Table 4.5. Comparison of mean ± SD pitching performance outcomes between the baseline and final sets.

	Baseline Set	Final Set	P Value	Δ
Performance Outcomes				
Average Ball Speed ($m.s^{-1}$)	29.5 ± 2.5	28.3 ± 2.5	**<0.001**	-4.1
Strike Pitches (%)	35.5 ± 14.0	32.8 ± 10.4	0.379	
Ball 1 Pitches (%)	45.1 ± 14.8	38.8 ± 15.9	0.204	
Ball 2 Pitches (%)	19.3 ± 10.0	28.4 ± 11.5	*0.053*	47.2

Note: Bold text identifies significant differences ($p < 0.05$). Italicised text identifies trends toward statistical significance ($p < 0.10$). Δ is the percent (%) change relative to the baseline set.

Table 4.6. Variability of the angular displacements at the balance position for the pitches of the baseline and final sets (ICC [95% Confidence Interval]).

	Baseline Set	Final Set
Leading Limb		
Hip Flexion	0.955 [0.900; 0.985]	0.949 [0.889; 0.983]
Hip Abduction	0.969 [0.931; 0.990]	0.947 [0.885; 0.982]
Hip External Rotation	0.863 [0.725; 0.952]	0.857 [0.714; 0.949]
Knee Flexion	0.888 [0.770; 0.961]	0.914 [0.819; 0.971]
Ankle Plantarflexion	0.949 [0.889; 0.983]	0.919 [0.828; 0.972]
Ankle Eversion	0.893 [0.779; 0.963]	0.839 [0.682; 0.942]
Foot Adduction	0.954 [0.899; 0.985]	0.922 [0.835; 0.973]
Foot Progression	0.957 [0.904; 0.985]	0.943 [0.876; 0.981]
Trailing Leg		
Hip Flexion	0.937 [0.863; 0.978]	0.928 [0.846; 0.975]
Hip Abduction	0.926 [0.842; 0.975]	0.900 [0791; 0.965]
Hip Internal/External Rotation	0.880 [0.755; 0.939]	0.771 [0.574; 0.914]
Knee Flexion	0.899 [0.789; 0.965]	0.953 [0.896; 0.984]
Ankle Dorsiflexion	0.825 [0.660; 0.937]	0.873 [0.741; 0.955]
Ankle Inversion/Eversion	0.722 [0.503; 0.893]	0.816 [0.645; 0.933]
Foot adduction	0.739 [0.528; 0.901]	0.803 [0.624; 0.928]
Foot Progression	0.919 [0.827; 0.972]	0.852 [0.704; 0.947]

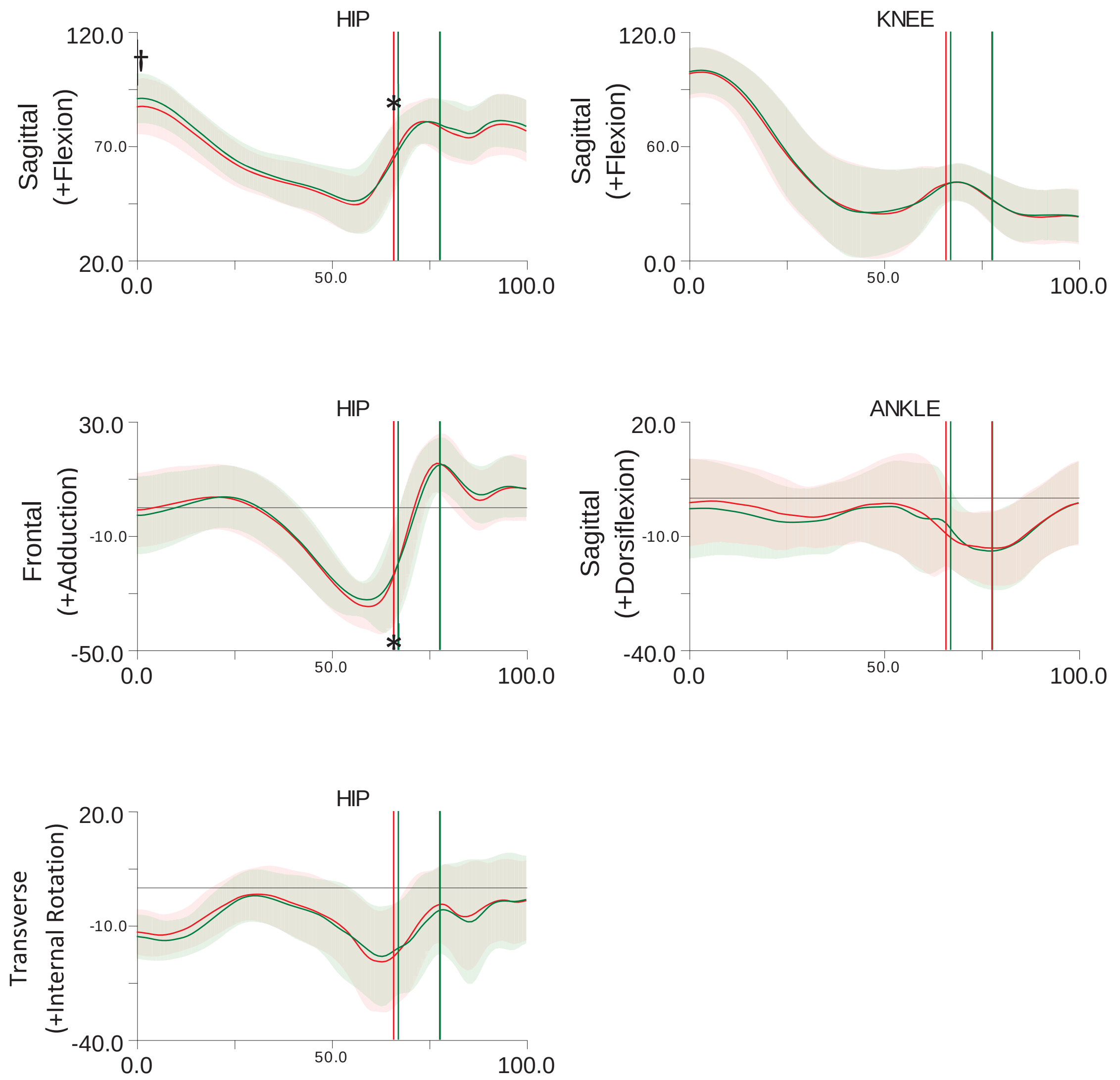

Fig. 4.1. Mean ± SD leading leg angular displacements (deg) during the baseline (green line) and final (red line) sets over the duration of the pitching cycle (% pitching cycle). Balance position occurs at 0% pitching cycle and maximal shoulder internal rotation occurs at 100% pitching cycle. The vertical lines at approximately 67% pitching cycle indicate when foot contact occurred during the baseline (green line) and final (red line) sets. The vertical lines at approximately 78% pitching cycle indicate when ball release occurred for the baseline and final sets. * indicates significant differences in the angular displacements between sets ($p < 0.05$). † indicates a trend towards a significant difference between sets ($p < 0.10$).

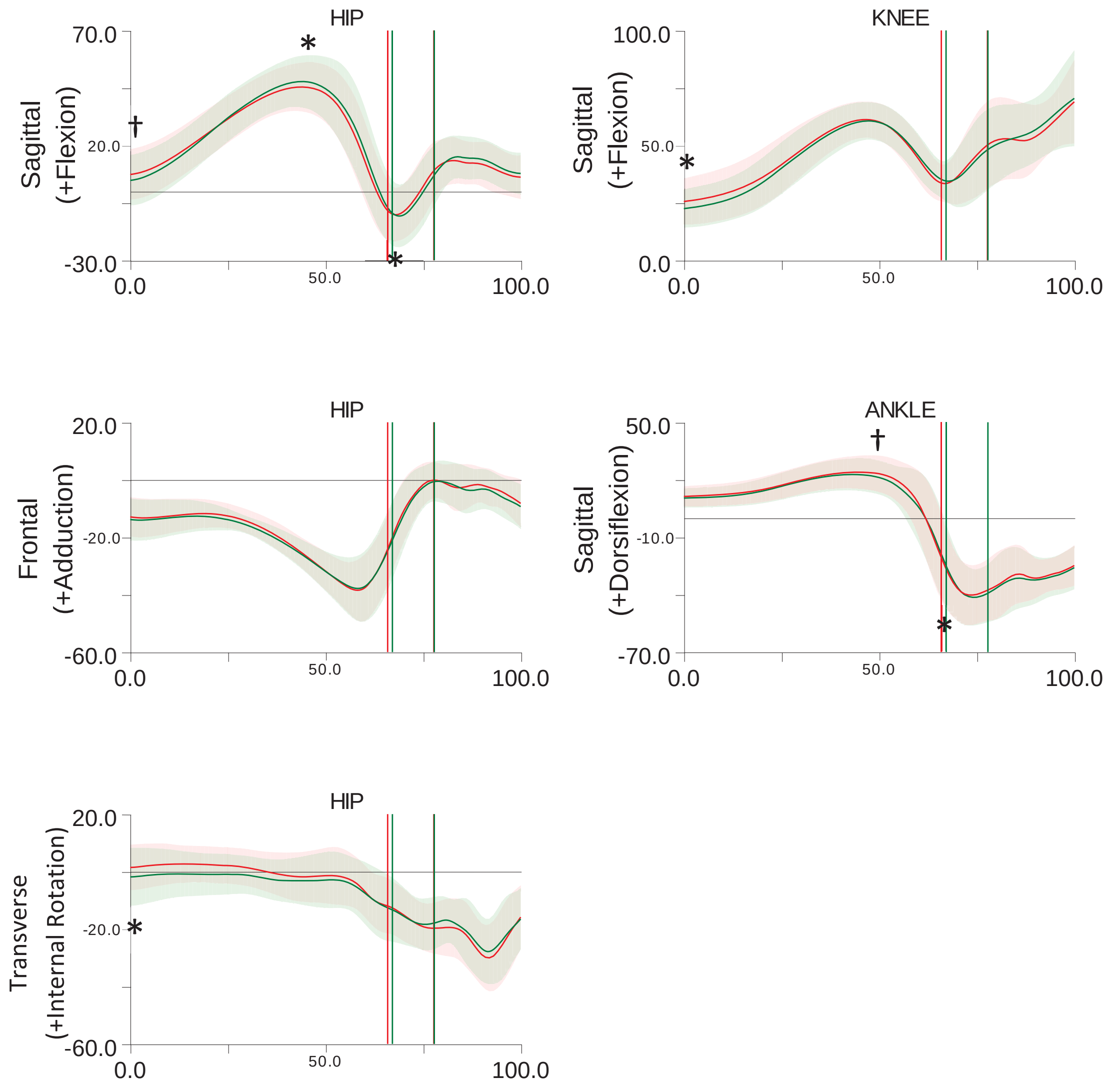

Fig. 4.2. Mean ± SD trailing leg angular displacements (deg) during the baseline (green line) and final (red line) sets over the duration of the pitching cycle (% pitching cycle). Balance position occurs at 0% pitching cycle and maximal shoulder internal rotation occurs at 100% pitching cycle. The vertical lines at approximately 67% pitching cycle indicate when foot contact occurred during the baseline (green line) and final (red line) sets. The vertical lines at approximately 78% pitching cycle indicate when ball release occurred for the baseline and final sets. * indicates significant differences between sets ($p < 0.05$). † indicates a trend towards a significant difference between sets ($p < 0.10$).

5. Discussion

This study primarily aimed to identify whether adolescent baseball pitchers changed lower extremity kinematic and temporal parameters during a simulated baseball game. Differences observed in the angular displacements at the balance position between the baseline and final sets are in support of hypothesis 1a. The decreases in the maximal angular velocities at the hip and knee during the stride phase between the baseline and final sets are in support of hypothesis 1d. Additionally, as the maximal hip extension and ankle plantarflexion angular velocities occurred later in the stride phase during the final set of pitches, these observations supported hypothesis 2. Hypothesis 1b was rejected as there were no significant differences in the leading knee extension angular displacements and velocities during the acceleration phase between the baseline and final sets of pitches. A lack of difference in the stride length between the two sets also resulted in the rejection of hypothesis 1c. Additionally, hypothesis 3 was rejected due to the lack of marked differences in the ICC values for the angular displacements at the balance position between the baseline and final sets.

The secondary outcome of the present study was to investigate whether performance outcomes changed during a simulated game. The results of this study are in support of the hypothesis as decreased performance outcomes were found in the final set of the simulated game, including decreased ball velocity. There was also a trend towards producing a greater percentage of Ball 2 pitches, indicating that pitchers threw more inaccurate pitches in the final set compared to their baseline performance. Furthermore, as Ball 2 pitches were classified as balls that completely missed the pitching net, it may also be inferred that the magnitude of pitching inaccuracy also increased by the end of the simulated game. The decreased performance outcomes observed at the end of the simulated game suggest that some form of fatigue was experienced as the pitchers were unable to maintain a consistent performance.

The changes in performance outcomes could be attributed to differences in the lower extremity kinematic and temporal parameters experienced in the final set of the simulated game.

5.1. Balance position

Consistent pitching mechanics are required to maintain fast and accurate pitches throughout a game [10, 12, 18]. Accordingly, pitchers exhibited low variability in the angular displacements for the trailing and leading legs at the balance position, as the majority of the ICC values in the baseline set were above 0.800 and 0.900, respectively. A consistent balance position may help maintain pitching performance as the balance position sets the rhythm for the rest of the pitching motion, including the sequencing of movements [4]. Therefore, consistency of the balance position may be critical for ensuring body segments are recruited in a proximal-to-distal order throughout a game. This order of recruitment is required to optimise the effect of the kinetic chain and maximise ball velocity [10]. In the final set of the simulated game, there were no marked differences in the ICC values for the angular displacements at the balance position compared to the pitches in the baseline set. These measurements of variability suggest that the pitchers adopted consistent kinematics at the balance position within each set, but not necessarily between sets.

While consistent kinematics at the balance position were adopted within each set, angular displacements were consistently different in the trailing and leading legs at the balance position between the baseline and final sets. These kinematic differences may have contributed to the reduced ball velocities observed in the final set of the simulated game. In the baseline set, the hip and knee of the trailing leg were slightly flexed at the balance position. This would require the hip and knee extensors to support the leg and assist with maintaining an upright posture. These extensor muscles would also drive the body towards the home plate during the stride phase [36]. However, at the end of the simulated game, the hip and knee of the trailing leg experienced more flexion at the balance position. The increased flexion suggests that the hip and knee extensors may have experienced muscular fatigue by the end of the simulated game and could not maintain an upright posture; however, assessing muscular fatigue was beyond the scope of this study. Therefore, muscular strength tests or assessments of muscle activity within these muscles need to be completed during a game to confirm whether muscular fatigue was experienced in the lower extremities.

During the wind-up phase, pitchers prepare for the stride by rotating the body away from the home plate into a closed position and raising the leading leg to approximately 90 degrees [8]. These preparatory movements result in the balance position and are used to increase the potential to generate energy [4]. In the present study, the trailing foot progression angle decreased in the final set relative to the baseline performance. Thus, greater internal rotation of the trailing hip was required to maintain the closed orientation of the upper body at the balance position. The compensatory change in hip internal rotation is further supported by the similar magnitudes of change at the foot and hip. However, the trailing hip remained more internally rotated throughout the majority of the stride phase, presumably due to the altered hip kinematics at the balance position. Conversely, the leading hip generated less flexion in the final set, indicating a decrease in potential to generate energy without any compensatory motion. It is possible that the pitchers experienced muscular fatigue and were unable to maintain the magnitude of hip flexion by the end of the simulated game. Consequently, this decreased potential energy in the leading leg could result in a decreased braking force produced upon foot contact. The braking force experienced upon foot contact has previously been positively correlated to ball velocity, as it provides the energy that is transferred through the kinetic chain [7, 9]. Therefore, the decreased hip flexion of the leading leg at the balance position may have contributed to the decrease in ball velocity observed in the final set of the simulated game.

5.2. Stride phase

In the baseline set, the pitchers achieved a stride length that equated to 77% of the pitchers' body height, which is similar to the recommended stride length of 80% body height [14, 17]. This stride length presumably reflects the optimal balance between the amount of forward momentum produced during the stride phase and the associated physiological demands [14, 22, 23]. However, different stride lengths have been reported for adolescent pitchers in previous studies [16, 17]. Milewski et al [16] observed an average stride length of 69% body height, whereas Fleisig et al [17] reported an average stride length of 85% body height. These differences between studies may be attributed to the different methods used to calculate stride length. The former study calculated stride length as the distance between the two ankle joint centres at the instant of foot contact [16]. This method may result in shorter stride lengths compared to the present study, as ankle plantarflexion of the trailing foot would theoretically move the trailing ankle joint centre closer to the leading ankle joint centre. Alternatively, the latter study measured stride length as the distance between the front edge of the pitching rubber and the joint centre of the leading ankle at foot contact [17]. Using the front edge of the pitching rubber as a reference point may result in slightly longer stride lengths than the present study, depending on the position of the ankle joint centre of the trailing foot relative to the pitching rubber. In the present study, stride length was calculated as the distance between the trailing ankle joint centre at the balance position and the leading ankle joint centre at foot contact. Therefore, it seems reasonable that the reported stride length in the present study falls within the range of stride length values previously reported.

Compared to the baseline performance, stride length was not significantly different in the final set of the simulated game. Similarly, no differences in stride length were observed in a previous study comparing the pitching mechanics of high velocity and low velocity pitchers [14]. However, foot contact occurred earlier in the pitching cycle in the final set compared to the baseline performance, resulting in a shortened stride phase duration. Consequently, kinematic differences in the leading leg were seen in the final set, including less hip flexion during the stride phase and at foot contact and more hip abduction at foot contact (Fig. 4.1). The decreased magnitude of leading hip flexion at foot contact may further suggest that fatigue was experienced in the hip flexors. Additionally, a shortened stride phase duration would presumably result in a more closed pelvis orientation at foot contact as there is less time to rotate the pelvis. Therefore, the leading leg may require greater hip abduction to maintain the desired leg orientation as it stretches out towards the home plate. These results suggest that it is not the stride length that may influence ball velocity, but rather the pitching mechanics that are used to achieve the desired stride length.

Pitchers also exhibited kinematic changes in the trailing leg during the stride phase of the final set, suggesting the drive towards the home plate decreased at the end of the simulated game. In the baseline set, the trailing hip and knee flexed while the ankle dorsiflexed in preparation for the explosive extension of the leg throughout the stride phase. In the final set, pitchers experienced less hip flexion and more ankle dorsiflexion compared to the baseline performance. Changes to the hip and ankle kinematics in the loading phase of the stride alter the potential to complete work at the hip and ankle. Accordingly, pitchers decreased the magnitudes of maximal hip extension and ankle plantarflexion in the final set (Fig 4.2). These decreased maximal angular displacements in the trailing leg suggest pitchers completed less work in the final set. Decreased work would result in less kinetic energy generated by the trailing limb to transmit up the kinetic chain, which would be detrimental to the acceleration of the ball. Furthermore, pitchers also exhibited decreased magnitudes of maximal hip abduction and knee extension angular velocities compared to the baseline set. The decreased angular velocities would directly reduce the amount of energy produced, thus contributing to the decreased ball velocity observed in the final set. These kinematic differences suggest that the trailing leg may have been affected by fatigue by the end of the simulated game. Further research is required to determine whether similar kinematic changes occur with accompanying decreases in the propulsive and braking forces produced during the stride phase and at foot contact, respectively.

Temporal parameters have been suggested to have a greater influence on ball velocity than kinematic parameters [11, 13, 14, 19, 21]. The timing of maximal joint angular velocities have been used to indicate when the body segments are recruited to contribute to the kinetic chain [10]. In the present study, recruitment of the trailing hip, knee and ankle in the sagittal plane during the stride phase followed the proximal-to-distal order in the baseline performance. This order of recruitment enables the pitchers to exploit the effects of the kinetic chain while the body is driven towards the home plate [10]. Pitchers maintained this order in the final set, but the maximal hip extension and ankle plantarflexion angular velocities occurred later in the stride phase compared to the baseline set. The relative delays observed in the timing of the maximal hip extension and ankle plantarflexion angular velocities equated to only 1.5% and 1.1% of the stride phase, respectively. As the duration of the stride phase was shorter in the final set, there may not have been differences in the absolute timing of these events. However, these relative delays in the timing of maximal angular velocities may result in pitchers achieving the maximal linear velocity of the centre of mass closer to the time of foot contact. In a previous study comparing high and low velocity pitchers, the low velocity pitchers had a tendency to achieve maximal linear velocity later in the stride phase, i.e. closer to foot contact [14]. However, linear velocity of the centre of mass was not calculated in this study and so it remains unknown whether the relative delays in the timing of maximal angular velocities influence when pitchers achieve maximal linear velocity or ball velocity. Future research is required to better understand the relationships between these temporal parameters and ball velocity.

5.3. Acceleration phase

Slower ball velocities have previously been associated with a longer arm cocking phase [48]. While the duration of the arm cocking phase was not included in the present study, the duration of the acceleration phase increased in the final set of the simulated game. This was inferred from the earlier occurrence of foot contact while there was no difference in the timing of ball release. A longer acceleration phase increases the amount of time for the braking forces to decelerate the linear velocity of the upper body leading up to ball release [22]. Due to the large braking forces experienced upon foot contact, the forward rotation of the shank rapidly decelerates while inertia maintains the linear movement of the upper body [40]. The combined actions of these movements results in knee extension. Slower ball velocities have been associated with greater flexion of the leading knee and deceased knee extension angular velocities [2, 3, 14]. However, pitchers did not exhibit any differences in the maximal knee extension angular velocity in the leading leg during the acceleration phase. Furthermore, no kinematic differences were seen at ball release that would suggest that the forward momentum of the upper body decreased in the final set. These observations suggest that the lower extremities primarily contribute to the acceleration of the ball during the wind-up and stride phases. Therefore, the main role of the lower extremities during the acceleration phase is to provide a stable base of support following leading foot contact.

The altered balance position and decreased propulsion of the body during the stride phase presumably resulted in decreased momentum produced prior to foot contact in the final set. Consequently, compensatory movements further up the kinetic chain may be required to contribute to the forward momentum of the body in the later phases of the pitching cycle. The increased hip abduction of the leading leg at foot contact may encourage greater contralateral trunk tilt in the final set. Excessive contralateral trunk tilt has been associated with increased ball velocities, presumably because greater trunk movement would contribute to the momentum of the upper body [60]. It has also been suggested that pitchers may exhibit greater contralateral trunk tilt due to muscle weakness, as gravity can assist trunk movement in the frontal plane [60]. Similarly, if pitchers sense that they did not produce a sufficient propulsive force during the stride phase, compensatory trunk movements may be adopted. However, encouraging greater contralateral trunk tilt in the final set may be detrimental to pitching accuracy. It has been suggested that forward trunk tilt influences the height of the ball release, whereas lateral trunk tilt may influence the trajectory of the ball in the horizontal plane [18]. Therefore, the altered hip kinematics of the leading leg may have indirectly influenced the decreased pitching accuracy observed in the final set of the simulated game. Promoting greater magnitudes of contralateral trunk tilt may also increase the risk of elbow injury, as contralateral trunk tilt of more than 10 degrees combined with greater shoulder abduction results in a larger maximal elbow varus torque [61]. However, further research is required to assess the trunk movements throughout a game in adolescent pitchers as trunk movements were not assessed in this study. Additionally, there is a lack of studies that have analysed the influence of pitching mechanics on pitching accuracy. Future research should investigate factors affecting pitching accuracy more thoroughly due to the importance of accuracy during baseball pitching.

5.4. Clinical implications

Collegiate pitchers have not exhibited fatigue in the hip musculature after pitching in a live baseball game [66]. However, younger pitchers may be more susceptible to fatigue during a baseball game. In the present study, the adolescent pitchers changed their lower extremity kinematics and were unable to maintain pitching performance at the end of the simulated game. Consequently, adolescent pitchers may need to strengthen the lower extremities to maintain the amount of momentum generated during the stride phase, which could help maintain the ball velocity produced throughout a game. Power activities such as sprints and standing jumps have previously been identified as predictors of ball velocity during baseball pitching [47]. Therefore, power training may be advantageous for improving pitching performance in adolescent pitchers, with a particular focus on the hip extensors and abductors, knee extensors and ankle plantarflexors in the trailing leg. Strengthening these muscles may enhance the ability to explosively extend the trailing leg and forcefully drive the body towards the home plate, thus increasing the amount of kinetic energy generated. Additionally, pitchers may need to strengthen the hip flexors to maintain the position of the leading leg at the balance position. Maintaining the amount of momentum generated in the early phases of the pitching cycle may also help to reduce the risk of injury in the throwing arm. Increased pitch counts have previously been correlated with decreased leading hip extension work and increased shoulder horizontal adduction work, suggesting pitchers develop a greater reliance on the throwing arm to accelerate the ball with fatigue [9].Therefore, pitchers may be able to avoid unnecessary and potentially injurious loads experienced at the shoulder and elbow by strengthening the lower extremities.

Lower extremity injuries during baseball pitching are less common than upper extremity injuries; however, the foot progression angle at foot contact may influence the risk of injury [9]. Specifically, an externally rotated leading foot at foot contact has the tendency to prematurely open the pelvis, which may increase the anterior shoulder force and medial elbow force, thus increasing the risk of shoulder and elbow injury [9]. While the pitchers tended to exhibit a slightly internally rotated foot progression angle at foot contact throughout the simulated game, the standard deviation for the foot progression angle was approximately 15 degrees in both sets. Therefore, some pitchers would have produced an unfavourable foot progression angle at foot contact. As there were no differences in the foot progression angle at foot contact between sets, this parameter may not be altered with extended play. However, some adolescent pitchers may be more susceptible to upper extremity injuries if they exhibit an externally rotated foot at foot contact. Therefore, coaches should be vigilant and ensure that their adolescent pitchers produce an internally rotated foot angle at foot contact to ensure the pelvis is not prematurely recruited. Premature pelvis recruitment may be detrimental to pitching performance and increase the risk of injury.

5.5. Limitations

The differences in the kinematic and temporal parameters were small in magnitude. The normal variation in the joint angular displacements within individuals during baseball pitching was reported to range between 1 – 5 degrees [18]. Ankle plantarflexion of the trailing leg was the only kinematic parameter that exhibited a difference greater than this range of normal variation, which suggests that this change may be the only parameter of clinical significance. As the hip and knee extensors are larger muscles groups than the ankle plantarflexors, they may have been more resistant to experiencing the effects of fatigue. Therefore, the upper extremities may have a greater influence on the decreased performance outcomes experienced with extended play, particularly as the role of the throwing arm is very demanding [30]. However, this was only a pilot study with a small sample size, which may have contributed to the small differences observed between the baseline and final sets and the large variability in the kinematics seen between participants (figures 4.1 and 4.2).

Different kinematic responses to the effects of extended play were observed between participants, which may have also contributed to the lack of clinically significant changes observed in this study. There did not appear to be trends in the changes in the kinematic parameters among the pitchers who had more years of pitching experience compared to those with fewer years of experience. Therefore, individual differences may have been influenced by training status and thus, their susceptibility to experience fatigue in the lower extremities. However, a training history and muscular strength tests were not collected, which may have revealed why some participants exhibited kinematic differences by the end of the simulated game, while others did not. The results of the present study may still be used to inform future investigators or pitching coaches of parameters that have a tendency to be affected by fatigue during baseball pitching in adolescent pitchers.

Some marker positions were largely interpolated throughout the pitching cycle, which needs to be taken into consideration when interpreting the results of this study. In particular, the leading side anterior superior iliac spine marker had large gaps of data missing while the leading leg was raised at the balance position and around the time of foot contact. This was presumably caused by the body blocking the view of the markers from the cameras. Additionally, participants were not required to wear compression shorts, which would have also contributed to the missing positional data of the markers. However, the accuracy of these interpolated marker positions were assessed relative to the positions of the reflective markers attached at the bony landmarks. Angular displacements of the hip in the three planes of motion were also compared using the pelvis segments that were created with the retro-reflective skin markers and with the interpolated anterior superior iliac spine markers. The sagittal and frontal planes of hip motion exhibited less than 5 degrees of error between the two pelvis models. This magnitude of error was within the range of normal variability previously reported [18]. Additionally, it is unknown how accurately the skin markers represent their respective bony landmarks due to skin movement artefact. Therefore, this magnitude of error was considered to be acceptable for the sagittal and frontal plane movements of the hip. However, the angular displacement of the hip in the transverse plane was less reliable when using the interpolated marker positions. The maximal magnitude of error for the angular displacement in the transverse plane was 8 degrees, which equated to approximately 33% of the total excursion of the hip in the transverse plane. Therefore, greater caution must be taken when interpreting the significance of the altered transverse plane hip motion. It is possible that previous research has come across similar problems with missing marker positional data due to the nature of the leading hip movement. Therefore, a more intensive marker set for the pelvis segment should be used, or a more reliable method to track the pelvis segment needs to be developed.

Pitching mechanics are usually only analysed for the strike pitches. However, the present study analysed the last five pitches of each set, regardless of pitching accuracy. This is a limitation of the present study as it is unknown whether the kinematic and temporal differences were related to the differences in ball velocity or pitching accuracy observed between the baseline and final sets. Analysing foot placement in the global coordinate system may have contributed to developing a better understanding of the factors influencing pitching accuracy. However, due to a lack of markers attached to the pitching net and pitching mound, this could not be analysed. Additionally, no correlational analysis was completed between the kinematic and temporal parameters with the performance outcomes. Such statistical analysis may have helped determine whether certain parameters influenced pitching accuracy and/or ball velocity during baseball pitching.

Another limitation of this study was the lack of measurements assessing muscular fatigue and/or subjective ratings of perceived exertion. This limits the ability to determine whether the changes in kinematic and temporal parameters were due to fatigue. Additionally, as participants did not compete in a live game, the pitchers may have lacked motivation to perform to their maximal capacity. This may have also influenced the decreased pitching performance outcomes observed in the final set. However, the kinematic and temporal differences and decreased performance outcomes observed in the final set suggest that some form of fatigue was experienced by the pitchers. Further analysis is required to confirm whether the lower extremities experienced muscular fatigue. To elicit fatigue, a previous study had collegiate pitchers complete sets of 15 pitches until they could no longer continue [20]. These collegiate pitchers completed 105-135 pitches before they reported fatigue. While this method may be suitable for collegiate pitchers, such pitch counts are not recommended for adolescent pitchers. Additionally, some pitchers may not continue pitching until reaching this magnitude of fatigue. Therefore, the recommended pitch count for adolescent pitchers was used to simulate a game in the present study, i.e. 90 pitches. While the participants may not have experienced volitional fatigue, the results provide insight into what parameters may require attention during extended play to maintain performance throughout a game. Additionally, the pitchers in the present study were younger than those in the previous study. Therefore, 90 pitches may have been sufficient to elicit some fatigue, particularly as ball velocity decreased in the final set of pitches.

6. Conclusion

Adolescent baseball pitchers exhibited kinematic and temporal changes, along with decreased performance outcomes at the end of the simulated game. Kinematic and temporal changes in the lower extremities primarily occurred at the balance position and throughout the stride phase. As the altered balance position seems to be the underlying factor of the kinematic changes throughout the stride phase, training sessions for baseball pitchers should have allocated time to practice consistently moving into the ideal balance position. Particular areas to focus on include the external rotation of the trailing foot so that it is parallel to the pitching rubber and lifting the leading leg until the thigh is at least parallel to the ground. By repetitively moving into the same balance position, pitchers would receive consistent proprioceptive feedback, which may help improve the consistency of the balance position throughout a game. As pitchers exhibited an altered balance position with extended play, it may be more effective to consciously work on the preparation of the balance position while physically and/or mentally fatigued. Ensuring that pitchers consistently move into the same balance position may prevent further kinematic and temporal changes in the pitching mechanics of the trunk and upper extremity. Coaches should also make sure not to neglect the conditioning of the lower extremities, particularly the trailing leg as it must forcefully drive the body towards the home plate. The majority of the research has focused on the pitching mechanics of the upper extremities between foot contact and maximum shoulder internal rotation. However, the results of the present study highlight the importance of the lower extremities and the wind-up and stride phases during baseball pitching.

7. References

[1] Olsen SJ, 2nd, Fleisig GS, Dun S, Loftice J, Andrews JR. Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. Am J Sports Med 2006; 34(6): 905-912.

[2] Escamilla RF, Fleisig GS, Barrentine SW, Zheng N, Andrews JR. Kinematic comparisons of throwing different types of baseball pitches. J Appl Biomech 1998; 14(1-23.

[3] Dun S, Loftice J, Fleisig GS, Kingsley D, Andrews JR. A Biomechanical Comparison of Youth Baseball Pitches Is the Curveball Potentially Harmful? Am J Sports Med 2008; 36(4): 686-692.

[4] Pappas AM, Zawacki RM, Sullivan TJ. Biomechanics of baseball pitching A preliminary report. Am J Sports Med 1985; 13(4): 216-222.

[5] Stodden DF, Langendorfer SJ, Fleisig GS, Andrews JR. Kinematic constraints associated with the acquisition of overarm throwing Part I: Step and trunk actions. Res Q Exerc Sport 2006; 77(4): 417-427.

[6] Fleisig GS, Barrentine SW, Escamilla RF, Andrews JR. Biomechanics of overhand throwing with implications for injuries. Sports Med 1996; 21(6): 421-437.

[7] MacWilliams BA, Choi T, Perezous MK, Chao EY, McFarland EG. Characteristic ground-reaction forces in baseball pitching. Am J Sports Med 1998; 26(1): 66-71.

[8] Elliott B, Grove JR, Gibson B. Timing of the lower limb drive and throwing limb movement in baseball pitching. International Journal of Sport Biomechanics 1988; 4(1): 59-67.

[9] Fortenbaugh D, Fleisig GS, Andrews JR. Baseball pitching biomechanics in relation to injury risk and performance. Sports Health 2009; 1(4): 314-320.

[10] Putnam CA. Sequential motions of body segments in striking and throwing skills: descriptions and explanations. J Biomech 1993; 26(Suppl 1): 125-135.

[11] Urbin MA, Fleisig GS, Abebe A, Andrews JR. Associations between timing in the baseball pitch and shoulder kinetics, elbow kinetics, and ball speed. Am J Sports Med 2013; 41(2): 336-342.

[12] Stodden DF, Fleisig GS, McLean SP, Andrews JR. Relationship of biomechanical factors to baseball pitching velocity: within pitcher variation. J Appl Biomech 2005; 21(1): 44-56.

[13] Stodden DF, Fleisig GS, McLean SP, Lyman SL, Andrews JR. Relationship of pelvis and upper torso kinematics to pitched baseball velocity. J Appl Biomech 2001; 17(2): 164-172.

[14] Matsuo T, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR. Comparison of kinematic and temporal parameters between different pitch velocity groups. J Appl Biomech 2001; 17(1): 1-13.

[15] Escamilla R, Fleisig G, Barrentine S, Andrews J, Moorman C, 3rd. Kinematic and kinetic comparisons between American and Korean professional baseball pitchers. Sports Biomech 2002; 1(2): 213-228.

[16] Milewski MD, Ounpuu S, Solomito M, Westwell M, Nissen CW. Adolescent baseball pitching technique: lower extremity biomechanical analysis. J Appl Biomech 2012; 28(5): 491-501.

[17] Fleisig GS, Barrentine SW, Zheng N, Escamilla RF, Andrews JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. J Biomech 1999; 32(12): 1371-1375.

[18] Fleisig G, Chu Y, Weber A, Andrews J. Variability in baseball pitching biomechanics among various levels of competition. Sports Biomech 2009; 8(1): 10-21.

[19] Dun S, Fleisig GS, Loftice J, Kingsley D, Andrews JR. The relationship between age and baseball pitching kinematics in professional baseball pitchers. J Biomech 2007; 40(2): 265-270.

[20] Escamilla RF, Barrentine SW, Fleisig GS, Zheng N, Takada Y, Kingsley D, Andrews JR. Pitching biomechanics as a pitcher approaches muscular fatigue during a simulated baseball game. Am J Sports Med 2007; 35(1): 23-33.

[21] Wight J, Richards J, Hall S. Influence of pelvis rotation styles on baseball pitching mechanics. Sports Biomech 2004; 3(1): 67-83.

[22] Ramsey DK, Crotin RL, White S. Effect of stride length on overarm throwing delivery: A linear momentum response. Hum Mov Sci 2014; 38(185-196.

[23] Crotin RL, Kozlowski K, Horvath P, Ramsey DK. Altered stride length in response to increasing exertion among baseball pitchers. Med Sci Sports Exerc 2014; 46(3): 565-571.

[24] Murray TA, Cook TD, Werner SL, Schlegel TF, Hawkins RJ. The effects of extended play on professional baseball pitchers. Am J Sports Med 2001; 29(2): 137-142.

[25] Lyman S, Fleisig GS, Andrews JR, Osinski ED. Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. Am J Sports Med 2002; 30(4): 463-468.

[26] Elliott B, Grove JR, Gibson B, Thurston B. A three-dimensional cinematographic analysis of the fastball and curveball pitches in baseball. International Journal of Sport Biomechanics 1986; 2(1): 20-28.

[27] Nissen CW, Westwell M, Ounpuu S, Patel M, Solomito M, Tate J. A biomechanical comparison of the fastball and curveball in adolescent baseball pitchers. Am J Sports Med 2009; 37(8): 1492-1498.

[28] Nissen CW, Westwell M, Ounpuu S, Patel M, Tate JP, Pierz K, Burns JP, Bicos J. Adolescent baseball pitching technique: a detailed three-dimensional biomechanical analysis. Med Sci Sports Exerc 2007; 39(8): 1347-1357.

[29] Dick R, Sauers EL, Agel J, Keuter G, Marshall SW, McCarty K, McFarland E. Descriptive epidemiology of collegiate men's baseball injuries: National Collegiate Athletic

Association Injury Surveillance System, 1988-1989 through 2003-2004. J Athl Train 2007; 42(2): 183-193.

[30] Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. Am J Sports Med 1995; 23(2): 233-239.

[31] Fleisig GS, Weber A, Hassell N, Andrews JR. Prevention of elbow injuries in youth baseball pitchers. Curr Sports Med Rep 2009; 8(5): 250-254.

[32] Oyama S. Baseball pitching kinematics, joint loads, and injury prevention. J Sport Health Sci 2012; 1(2): 80-91.

[33] Dillman CJ, Fleisig GS, Andrews JR. Biomechanics of pitching with emphasis upon shoulder kinematics. J Orthop Sports Phys Ther 1993; 18(2): 402-408.

[34] Sabick MB, Kim Y-K, Torry MR, Keirns MA, Hawkins RJ. Biomechanics of the Shoulder in Youth Baseball Pitchers Implications for the Development of Proximal Humeral Epiphysiolysis and Humeral Retrotorsion. Am J Sports Med 2005; 33(11): 1716-1722.

[35] Tippett SR. Lower extremity strength and active range of motion in college baseball pitchers: a comparison between stance leg and kick leg. J Orthop Sports Phys Ther 1986; 8(1): 10-14.

[36] Campbell BM, Stodden DF, Nixon MK. Lower extremity muscle activation during baseball pitching. J Strength Cond Res 2010; 24(4): 964-971.

[37] Morriss C, Bartlett R. Biomechanical factors critical for performance in the men's javelin throw. Sports Med 1996; 21(6): 438-446.

[38] Ferdinands R, Marshall RN, Kersting U. Centre of mass kinematics of fast bowling in cricket. Sports Biomech 2010; 9(3): 139-152.

[39] Lin HT, Su FC, Nakamura M, Chao EY. Complex chain of momentum transfer of body segments in the baseball pitching motion. J Chin Inst Eng 2003; 26(6): 861-868.

[40] Guido JA, Jr., Werner SL. Lower-extremity ground reaction forces in collegiate baseball pitchers. J Strength Cond Res 2012; 26(7): 1782-1785.

[41] Fleisig CS, Escamilla RF, Andrews JR, Matsuo T, Barrentine SW. Kinematic and Kinetic Comparison Between Baseball Pitching and Football Passing. J Appl Biomech 1996; 12(2): 207-224.

[42] Feltner M. Dynamics of the shoulder and elbow joints of the throwing arm during a baseball pitch. International Journal of Sports Biomechanics 1986; 2(235-259.

[43] DiGiovine NM, Jobe FW, Pink M, Perry J. An electromyographic analysis of the upper extremity in pitching. J Shoulder Elbow Surg 1992; 1(1): 15-25.

[44] Jobe FW, Moynes DR, Tibone JE, Perry J. An EMG analysis of the shoulder in pitching. A second report. Am J Sports Med 1984; 12(3): 218-220.

[45] Jobe FW, Tibone JE, Perry J, Moynes D. An EMG analysis of the shoulder in throwing and pitching. A preliminary report. Am J Sports Med 1983; 11(1): 3-5.

[46] Neal RJ, Snyder Jr CW, Kroonenberg PM. Individual differences and segment interactions in throwing. Hum Mov Sci 1991; 10(6): 653-676.

[47] Nakata H, Nagami T, Higuchi T, Sakamoto K, Kanosue K. Relationship between performance variables and baseball ability in youth baseball players. J Strength Cond Res 2013; 27(10): 2887-2897.

[48] Werner SL, Suri M, Guido JA, Jr., Meister K, Jones DG. Relationships between ball velocity and throwing mechanics in collegiate baseball pitchers. J Shoulder Elbow Surg 2008; 17(6): 905-908.

[49] Yamada Y, Yamashita D, Yamamoto S, Matsui T, Seo K, Azuma Y, Kida Y, Morihara T, Kimura M. Whole-body and segmental muscle volume are associated with ball velocity in high school baseball pitchers. Open Access J Sports Med 2013; 4(89-95.

[50] Fleisig GS, Kingsley DS, Loftice JW, Dinnen KP, Ranganathan R, Dun S, Escamilla RF, Andrews JR. Kinetic comparison among the fastball, curveball, change-up, and slider in collegiate baseball pitchers. Am J Sports Med 2006; 34(3): 423-430.

[51] Yeow CH, Lee PV, Goh JC. Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. Knee 2010; 17(2): 127-131.

[52] Oyama S, Yu B, Blackburn JT, Padua DA, Li L, Myers JB. Improper trunk rotation sequence is associated with increased maximal shoulder external rotation angle and shoulder joint force in high school baseball pitchers. Am J Sports Med 2014; 42(9): 2089-2094.

[53] Oliver GD, Keeley DW. Pelvis and torso kinematics and their relationship to shoulder kinematics in high-school baseball pitchers. J Strength Cond Res 2010; 24(12): 3241-3246.

[54] Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. J Appl Biomech 2007; 23(1): 42-51.

[55] Aguinaldo AL, Chambers H. Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. Am J Sports Med 2009; 37(10): 2043-2048.

[56] Davis JT, Limpisvasti O, Fluhme D, Mohr KJ, Yocum LA, Elattrache NS, Jobe FW. The effect of pitching biomechanics on the upper extremity in youth and adolescent baseball pitchers. Am J Sports Med 2009; 37(8): 1484-1491.

[57] Zaremski JL, Krabak BJ. Shoulder injuries in the skeletally immature baseball pitcher and recommendations for the prevention of injury. PM R 2012; 4(7): 509-516.

[58] Hirashima M, Kadota H, Sakurai S, Kudo K, Ohtsuki T. Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. J Sports Sci 2002; 20(4): 301-310.

[59] Toyoshima S, Hoshikawa T, Miyashita M, Oguri T. Contribution of the body parts to throwing performance. International series on sports sciences 1974; 1(169-174.

[60] Oyama S, Yu B, Blackburn JT, Padua DA, Li L, Myers JB. Effect of excessive contralateral trunk tilt on pitching biomechanics and performance in high school baseball pitchers. Am J Sports Med 2013; 41(10): 2430-2438.

[61] Matsuo T, Fleisig GS. Influence of shoulder abduction and lateral trunk tilt on peak elbow varus torque for college baseball pitchers during simulated pitching. J Appl Biomech 2006; 22(2): 93-102.

[62] Stodden DF, Langendorfer SJ, Fleisig GS, Andrews JR. Kinematic constraints associated with the acquisition of overarm throwing Part II: Upper extremity actions. Res Q Exerc Sport 2006; 77(4): 428-436.

[63] Brown LP, Niehues SL, Harrah A, Yavorsky P, Hirshman HP. Upper extremity range of motion and isokinetic strength of the internal and external shoulder rotators in major league baseball players. Am J Sports Med 1988; 16(6): 577-585.

[64] Anloague PA, Spees V, Smith J, Herbenick MA, Rubino LJ. Glenohumeral range of motion and lower extremity flexibility in collegiate-level baseball players. Sports Health 2012; 4(1): 25-30.

[65] Baechle TR, Earle RW. Essentials of strength training and conditioning. 3rd ed. Champaign, IL : Human Kinetics; 2008.

[66] Mullaney MJ, McHugh MP, Donofrio TM, Nicholas SJ. Upper and lower extremity muscle fatigue after a baseball pitching performance. Am J Sports Med 2005; 33(1): 108-113.

[67] Benjaminse A, Habu A, Sell TC, Abt JP, Fu FH, Myers JB, Lephart SM. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. Knee Surg Sports Traumatol Arthrosc 2008; 16(4): 400-407.

[68] Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett WE, Yu B. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. Am J Sports Med 2005; 33(7): 1022-1029.

[69] Coventry E, O'Connor KM, Hart BA, Earl JE, Ebersole KT. The effect of lower extremity fatigue on shock attenuation during single-leg landing. Clin Biomech (Bristol, Avon) 2006; 21(10): 1090-1097.

[70] Abrams GD, Safran MR. Diagnosis and management of superior labrum anterior posterior lesions in overhead athletes. Br J Sports Med 2010; 44(5): 311-318.

[71] Kontaxis A, Cutti A, Johnson G, Veeger H. A framework for the definition of standardized protocols for measuring upper-extremity kinematics. Clin Biomech (Bristol, Avon) 2009; 24(3): 246-253.

[72] Motion Analysis Corporation. OrthoTrak 6.6 Reference Manual. Santa Rosa, CA: 2009.