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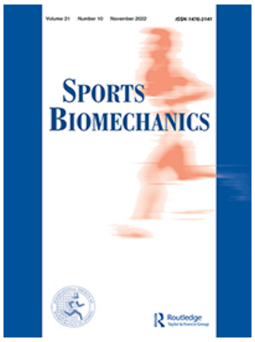
DOI
10.1080/14763141.2022.2129430

Publication date
2022

Document Version
Final published version

Published in
Sports Biomechanics



Sports Biomechanics

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rspb20

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To cite this article: Anne F.M.J. de Swart, Bart van Trigt, Kyle Wasserberger, Marco J.M. Hoozemans, DirkJan H.E.J. Veeger & Gretchen D. Oliver (2022): Energy flow through the lower extremities in high school baseball pitching, Sports Biomechanics, DOI: 10.1080/14763141.2022.2129430

To link to this article: https://doi.org/10.1080/14763141.2022.2129430

Published online: 13 Oct 2022.

SPORTS BIOMECHANICS
https://doi.org/10.1080/14763141.2022.2129430

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Energy flow through the lower extremities in high school baseball pitching

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ABSTRACT

It is generally accepted that most of the energy transferred to the ball during a baseball pitch is generated in the trunk and lower extremities. Therefore, purpose of this study was to assess the energy flow through the lower extremities during a baseball pitch. It was hypothesised that the (stabilising) leading leg mainly transfers energy in a distal-to-proximal order as a kinetic chain while the (driving) trailing leg generates most energy, primarily at the hip. A joint power analysis was used to determine the rates of energy (power) transfer and generation in the ankles, knees, hips and lumbosacral joint (L5-S1) for 22 youth pitchers. Analyses showed that the leading leg mainly transfers energy upwards in a distal-to-proximal order just before stride foot contact. Furthermore, energy generation was higher in the trailing leg and primarily arose from the trailing hip. In conclusion, the legs contribute differently to the energy flow where the leading leg acts as an initial kinetic chain component and the trailing leg drives the pitch by generating energy. The actions of both legs are combined in the pelvis and passed on to the subsequent, more commonly discussed, open kinetic chain starting at L5-S1.

ARTICLE HISTORY
Received 14 December 2021
Accepted 22 September 2022

KEYWORDS
Power transfer; power generation; kinetic chain; lower body; biomechanics

Introduction

A successful baseball pitch is facilitated by high ball speed, which, in practice, requires the input of as much energy as possible into the ball up to ball release. It is generally accepted that the sequence and timing of movements in the kinetic chain is used to generate energy in the lower extremities and trunk and sequentially transfer this energy up the kinetic chain to the ball through the throwing arm (Chu et al., 2016; Kobayashi et al., 2013; Seroyer et al., 2010; Shimada et al., 2004). This generation and transfer of energy is called 'energy flow' and is defined as two components: (1) the generation and absorption of energy by muscles at the joints and (2) the transfer of energy between the segments (Martin et al., 2014). It is important to understand energy flow, as this can help pitchers

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optimise the energy delivery to the ball to reach higher ball speeds and thus improve their performance.

The examination of energy flow has recently gained popularity as it provides a comprehensive and quantitative assessment of the efficiency of the pitching motion instead of isolating individual orthogonal components of kinematic or kinetic variables, as has traditionally been done (Aguinaldo & Escamilla, 2019; Howenstein et al., 2019; Martin et al., 2014; Naito et al., 2011; Roach & Lieberman, 2014; Shimada et al., 2004). Various studies have already studied the energy flow during a baseball pitch. In these studies, it was found that most of the energy used to accelerate the throwing arm segments was generated and transferred by the trunk, implying that the rapid motions of the distal segments in the kinetic chain are mainly caused by energy produced in the larger proximal segments, being the trunk and pelvis (Howenstein et al., 2019; Naito et al., 2011; Roach & Lieberman, 2014). Furthermore, according to the kinetic chain theory, the timing of energy transfer through each joint is essential for reaching high ball speed (Putnam, 1993; Seroyer et al., 2010). Although these studies provide important insights into the energy flow during baseball pitching, the lower extremities are often not considered.

The lower extremities probably play a key role in the energy flow during the pitch, since they initiate the pitching motion with powerful and dynamic actions. It is therefore suggested that the lower extremities form an initial and essential source of energy generation (Burkhart et al., 2003; Chu et al., 2016; Kibler, 1995; Seroyer et al., 2010). It is assumed that the trailing leg is the driver of the pitching motion, as this leg pushes the body forward towards the home plate (Elliott et al., 1988; Howenstein et al., 2020; MacWilliams, Choi, Perezous, Chao, & McFarland, 1998; Ryan & Torre, 1977). After foot contact, the leading leg has to form a stable base to support the subsequent rotations of the pelvis, trunk and throwing arm segments (Burkhart et al., 2003; Elliott et al., 1988; Howenstein et al., 2020). With these actions, the lower extremities form a special component of the kinetic chain during a baseball pitch and possibly even a separate kinetic chain as a base for the open kinetic chain starting at L5-S1, as was also defined by Van der Graaff (2019). However, how the actions of the trailing and leading leg translate to the energy flow through the lower extremities during a baseball pitch has not yet been investigated.

One previous study has partially examined the energy flow through the lower extremities during pitching and revealed that most of the energy used to accelerate the pelvis, trunk and distal arm segments was generated at the hips (Roach & Lieberman, 2014). However, this study only included the hips and merely assessed energy generation and not energy transfer. Although this study provided an initial insight, their findings do not fully describe the energy flow through the lower extremities. Therefore, in the current study, a complete, 3-dimensional energy flow analysis of the lower extremities will be performed based on the joint power analysis described by Robertson and Winter (1980). This will allow to determine the separate energy transfer and generation at each joint produced by the acting joint forces and torques (Howenstein et al., 2019; Robertson & Winter, 1980).

The purpose of this study is to examine the energy flow, and its components of transfer and generation, through the lower extremities during a baseball pitch. It is hypothesised that the leading leg does not generate or absorb much energy, as it has to minimise joint motions to form a stable base. Instead, it is expected that this leg would be more involved in transferring energy up the kinetic chain just after foot contact in a distal-to-proximal joint order from the ground up towards L5-S1. Furthermore, it is hypothesised that the trailing leg generates most of the energy in the lower extremities, primarily at the hip, as this leg is assumed to be the main driver of the pitching motion.

Methods

Participants

Twenty-two high school baseball pitchers (age 16.2 ± 0.8 years; body height 1.80 ± 0.49 m; body weight 75.0 ± 7.9 kg; ball speed 32.9 ± 2.3 m/s (73.7 ± 5.1 mph)) participated in this study. Inclusion criteria for these participants were (1) coach recommendation, to ensure that all participants were competitively active as pitcher, (2) no history of surgery to the upper extremity, and (3) no upper extremity injuries in the past six months. None of the participants reported to have suffered any injury or to have experienced any pain or stiffness in their upper or lower extremity following extensive throwing sessions within the past year.

Procedures

All testing protocols were approved by The Institutional Review Board of Auburn University. Prior to testing, all procedures were explained to each participant and their guardian(s) after which written informed assent and consent were obtained. Participants were instructed not to throw or engage in vigorous physical activity for a day prior to testing. All measurements were performed in the indoor Sports Medicine and Movement Laboratory at Auburn University to provide a controlled environment. Once participants were equipped with the sensors, they were given an unlimited amount of time to become familiar with the sensors and to perform their warm-up routine as usual before full-effort pitching (on average 10 minutes). The participants wore athletic shorts and a loose-fitting shirt to allow for unobstructed access to the locations for sensor placement. They also wore their catching glove to mimic the game situation as much as possible. When the warm-up was complete, participants performed three full-effort fastball pitches for strikes from the pitching mound to a catcher over an age-appropriate regulation distance (60 ft; 18.44 m). Participants were instructed to throw from the wind-up position.

Data acquisition

Kinematic data were collected with the MotionMonitor software (Innovative Sports Training, Chicago, IL, USA) synchronised with an electromagnetic tracking system (trakSTAR, Ascension Technologies Inc., Burlington, VT, USA). The position and orientation of fourteen electromagnetic sensors (Flock of Birds, Ascension Technologies Inc., Burlington, VT, USA) were collected in the global coordinate system at a sample frequency of 238 Hz. All sensors were mounted on the participant's skin using double-sided adhesive tape and were then wrapped with PowerFlex cohesive stretch tape (Andover Healthcare Inc., Salisbury, MA, USA). A full-body data acquisition

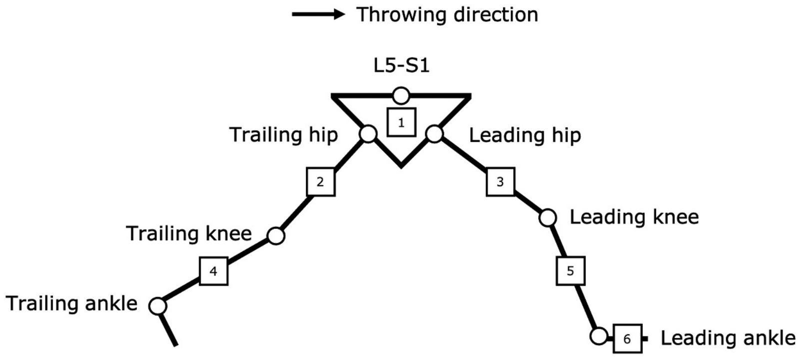


Figure 1. Linked-segment model of the lower extremities including sensor locations for a right-handed pitcher. The numbers indicate the sensor number. An additional sensor was used for pointering landmarks.

was performed but only the data obtained from the lower extremities were used for this study. The locations of the sensors are depicted in Figure 1. An additional sensor was rigidly affixed to a stylus for the digitisation of bony landmarks to develop a linked-segment model of the body consistent with recommendations of the International Society of Biomechanics (Wu et al., 2002, 2005). Ground reaction force data were collected at 1200 Hz using two in-ground force plates (Bertec 4060 NC; Bertec Corp., Columbus, OH, USA), one embedded into a pitching mound and the other just in front of the mound in the leading foot's landing area.

Data processing

For each participant, the fastest pitch was selected for analysis. Raw data regarding sensor position and orientation were filtered using a second-order, Butterworth low-pass filter with a cut-off frequency of 10 Hz. Based on the pointered landmark data, the joint centres of the ankles and knees were determined as the midpoint between their medial and lateral aspects. The hip joint centre was estimated using the Bell method (Bell et al., 1990). Anthropometric parameters were obtained from Zatsiorsky and Seluyanov (1983). The time series of relevant kinematic and kinetic variables were computed using equations embedded in The MotionMonitor software and were then exported and processed for further analysis (Gagnon & Gagnon, 1992).

To delineate the time course of the pitching motion, specific events in the time series were determined: peak knee height, stride foot contact, maximal external rotation, and ball release. Peak knee height (PKH) was defined as the maximal vertical position of the leading knee. Stride foot contact (SFC) was defined as the first frame where a non-zero ground reaction force was observed for the leading foot. Maximal external rotation (MER) at the shoulder joint was identified as the local minimum (right-handed pitchers) or maximum (left-handed pitchers) of the axial rotation of the throwing-side humerus relative to the thorax (Wu et al., 2005). Ball release (BR) was defined to be coincident with the peak resultant angular velocity of the throwing-side hand.

Calculation of energy flow

The calculation of energy flow was performed in MATLAB 2020a (The MathWorks Inc., Natick, MA, USA) using a 3-dimensional linked-segment model composed of shanks, thighs, and pelvis (Figure 2). The included joints in this model were the ankles, knees, and hips of the leading and trailing leg as well as the lumbosacral joint, which was defined as L5-S1. All calculations were performed in the global coordinate system.

To investigate energy flow, the rate of energy flow (power) was calculated using a joint power analysis as described in Robertson and Winter (1980). Net joint reaction forces and net joint torques act on each segment, thereby delivering power to the segments and creating a flow of energy through the joints. In this analysis, the power delivered by net joint reaction forces and net joint torques *on the segments* is calculated over time, which are then sorted per joint and further partitioned into time series of power transfer and generation/absorption *through the joints*. In this analysis, it is assumed that translation within joints is not possible and that joint torques are caused by muscles alone (Robertson & Winter, 1980).

The power delivered by a net joint reaction force (joint force power; JFP) was calculated as the scalar product of the net joint reaction force at joint i on segment j ($\vec{F}_{i,j}$) and the linear velocity of the joint centre ($\vec{v}_i$):

$$JFP = \vec{F}_{i,j} \cdot \vec{v}_i \tag{1}$$

The two JFPs at a joint are equal but opposite in sign. This represents an exchange of energy; the rate at which one joint force generates energy to one segment is equivalent to

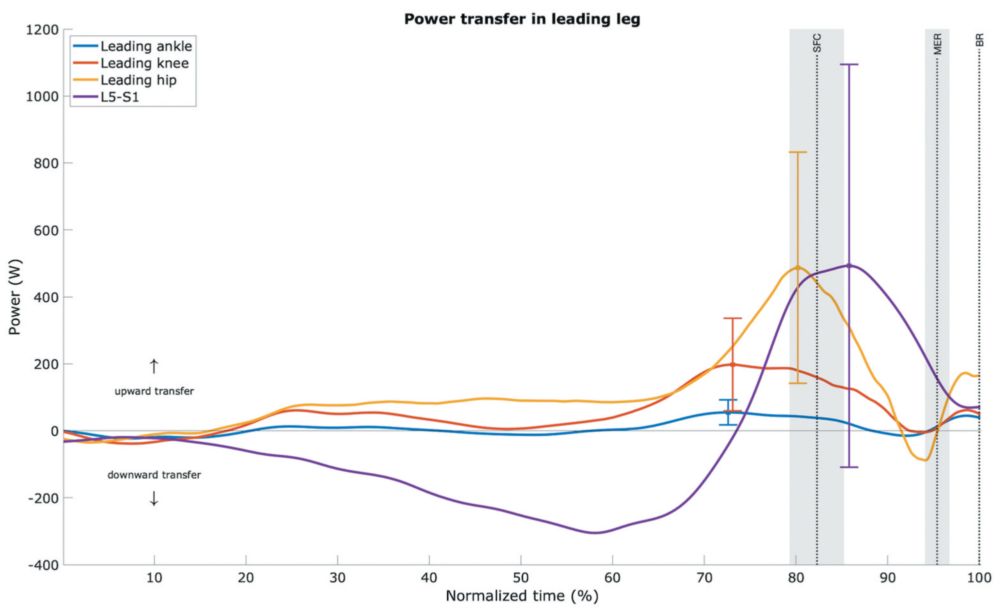


Figure 2. Mean normalised power transfer time series for the leading leg joints and L5-S1 for all participants. The asterisks depict the estimated peaks of the mean power transfer time series. The vertical dotted lines depict the mean timing of the events of SFC, MER, and BR (±1 SD shown by the grey area).

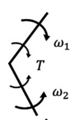
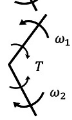
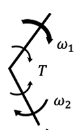
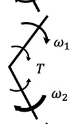
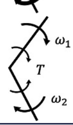
the rate at which the other joint force absorbs energy from the adjacent segment (Robertson & Winter, 1980). Thus, joint forces act as a mechanism of energy transfer between adjacent segments.

The power delivered by a net segment torque/joint torque (segment torque power; STP) was computed as the scalar product of the net joint torque at joint i on segment j ($\vec{T}_{i,j}$) and the angular velocity of segment j ($\vec{\omega}_j$):

$$STP = \vec{T}_{i,j} \cdot \vec{\omega}_j \tag{2}$$

The two joint torques at each joint are equal in magnitude but opposite in sign, but the angular velocities of two adjacent segments are not necessarily the same. Therefore, the two STPs at each joint most likely have different values, resulting in multiple possible patterns of energy flow (Robertson & Winter, 1980; Table 1). Joint torques can act as a mechanism of energy transfer as well as a mechanism of energy generation or absorption, depending on the relative signs of the adjacent STPs. When the STPs have the same sign or when one STP is zero, the muscles at that joint are merely generating or absorbing energy. The total rate of energy generation or absorption (hereafter referred to as just *energy generation*) is then defined as the sum of the adjacent STPs. Conversely, when the adjacent STPs have opposite signs, the muscles at that joint are also transferring energy. In this case, the smallest STP represents the rate at which energy is transferred and the relative difference between the two STPs represents the rate at which energy is generated or absorbed.

Table 1. Patterns of power generation, absorption, and transfer for two adjacent segments. Adapted from: Robertson and Winter (1980). Mechanical energy generation, absorption and transfer amongst segments during walking. Journal of biomechanics, 13(10), 845–854.

	Type of contraction	STPs	Muscle function	Amount, type and direction of power
Same sign				
Both positive/ one positive and one equal to zero	Concentric		Power generation	$T \cdot \omega_1$ generated to segment 1 $T \cdot \omega_2$ generated to segment 2
Both negative/ one negative and one equal to zero	Eccentric		Power absorption	$T \cdot \omega_1$ absorbed from segment 1 $T \cdot \omega_2$ absorbed from segment 2
Opposite sign				
STP on segment 1 highest ($T \cdot \omega_1 > T \cdot \omega_2$)	Concentric		Power generation and transfer	$T \cdot (\omega_1 - \omega_2)$ generated to segment 1 $T \cdot \omega_2$ transferred from segment 2 to segment 1
STP on segment 2 highest ($T \cdot \omega_1 < T \cdot \omega_2$)	Eccentric		Power absorption and transfer	$T \cdot (\omega_2 - \omega_1)$ absorbed from segment 2 $T \cdot \omega_1$ transferred from segment 2 to segment 1
STPs equal ($T \cdot \omega_1 = T \cdot \omega_2$)	Isometric (dynamic)		Power transfer	$T \cdot \omega_2$ transferred from segment 2 to segment 1

T = joint torque, ω_1 = angular velocity of segment 1, ω_2 = angular velocity of segment 2.

The calculated JFP and STP time series were used to describe the energy transfer and generation at the ankles, knees, and hips of the leading and trailing leg as well as L5-S1. Due to skin deformations and model inaccuracies, the two JFPs at one joint are not equivalent. Therefore, for the joints where time series of both JFPs were available (e.g., the knees and hips), the two JFPs were averaged to estimate the power transfer by the joint force. For the joints where only one JFP was available (e.g., ankles and L5-S1), only this JFP was used for the power transfer by joint force.

The net power transfer was defined as the sum of the power transfer by the joint force and the power transfer by the joint torque. The net power transfer was calculated for all joints in the linked-segment model and was calculated in such a way that power transfer was positive when the transfer was directed up the kinetic chain. Power generation was calculated only for the knees and hips since the two STPs that are necessary to calculate the separated power transfer and generation by STPs were not available for the other joints (e.g., ankles and L5-S1).

To assess the amount of energy transfer and generation during the pitch, the peaks of the power transfer and power generation time series were estimated. First, the local maxima in the time series were identified. Subsequently, a second-order polynomial function was fitted to the data around the local maxima (range of seven samples) to accurately estimate (the timing of) the peak values of power transfer and power generation.

To allow for a fair comparison between pitchers, the resulting power transfer and power generation time series were normalised in time from PKH to BR. Furthermore, the individual normalised time series were used to calculate the average normalised time series of power transfer and generation per joint over pitchers. Based on the individual normalised time series, the timing of the peak power transfer in each joint was determined and averaged over pitchers.

Statistical analysis

Parameters of interest included peak positive power transfer, normalised timing of peak positive power transfer, and peak positive power generation. For comparison between joints, a dependent-samples t-test was used. The significance level was set at $p = 0.05$ and all statistical analyses were performed in IBM SPSS Statistics 27.

Results

The pitches of two participants were excluded due to invalid data. Data from the twenty remaining participants were used to analyse the power transfer and power generation in the lower extremities.

Power transfer

Peak power transfer increased progressively over the joints from the leading ankle to L5-S1 (Figure 2). In the leading ankle, knee, and hip, the power transfers primarily had positive values. In L5-S1, the power transfer had negative values for most of the stride phase. Towards SFC, the power transfer in L5-S1 became positive and remained positive for the duration of the pitch. The power transfer showed a peak first at the leading ankle, followed by successive peaks at the knee, leading hip, and L5-S1. The peak power transfers in the leading ankle, knee, and hip all occurred before SFC, whereas the peak power transfer in L5-S1 occurred just after SFC.

In all joints, the mean normalised timings occurred at the end of the stride phase, just before SFC (Figure 3). There is a high amount of variation in the mean normalised timing in each joint as can be seen by the horizontal error bars. The horizontal error bars of all joints show overlap with each other and, in addition, the horizontal error bars of the peak power transfer timings in the leading hip and L5-S1 overlap with the standard deviation of SFC timing.

In the trailing leg, no progressive increase in peak power transfer over the joints was observed since the peak power transfer in the trailing ankle is higher than the peak power transfer in the trailing knee (Figure 4). In the trailing knee, hip, and L5-S1, the power transfer was mainly negative during the stride phase. Towards SFC, the power transfer in the trailing hip and L5-S1 became positive while the power transfer in the trailing knee remained negative until just before BR. In the trailing ankle, the power transfer remained positive for most of the time. The first peak power transfer occurred at the trailing ankle, followed by peaks at the trailing hip, L5-S1, and finally at the trailing knee. The power transfer in the trailing ankle peaks before SFC, the peak power transfers in the trailing hip and L5-S1 just after SFC, and the peak power transfer in the trailing knee around BR. Since no clear order was observed in the peak power transfers in the trailing leg, the timing was not further examined.

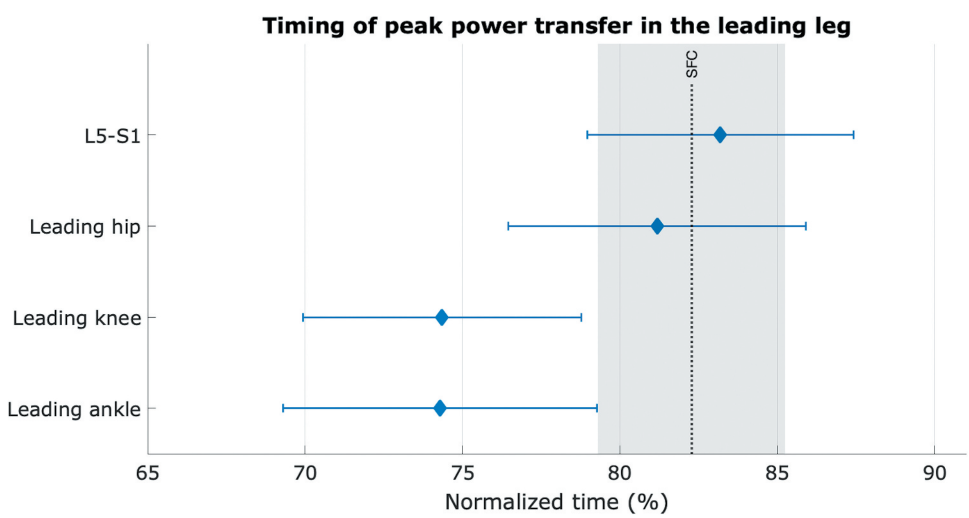


Figure 3. Mean normalised timing of the peak power transfer for the leading leg joints and L5-S1 for all participants. Diamonds depict the mean normalised timing (±1 SD depicted per group by the error bars). The mean normalised timing of SFC is shown by the vertical dotted line (±1 SD for all participants shown by the grey area).

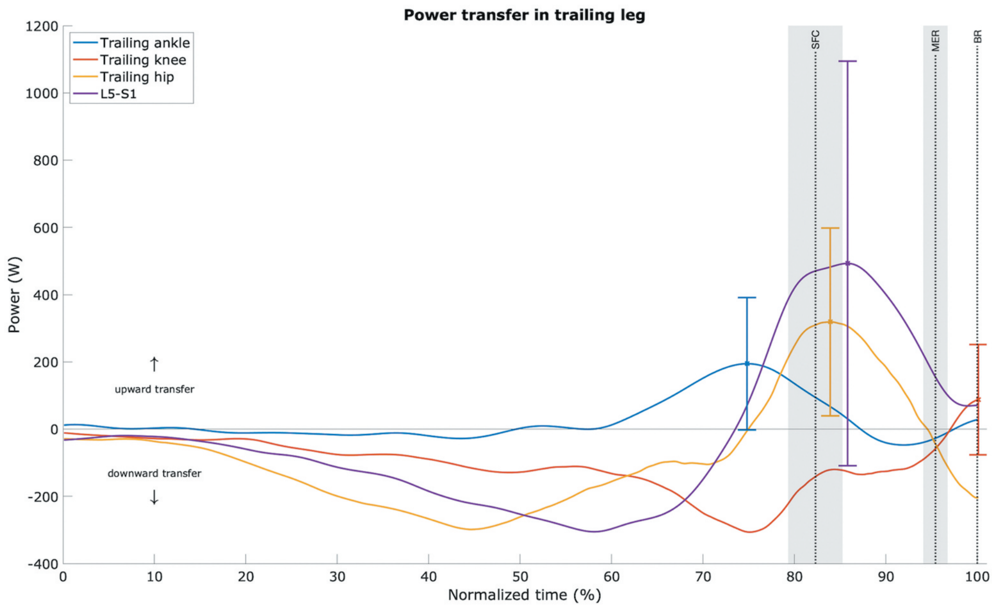


Figure 4. Mean normalised power transfer time series for the trailing leg joints and L5-S1 for all participants. The asterisks depict the estimated peaks of the mean power transfer time series. The vertical dotted lines depict the mean timing of the events of SFC, MER, and BR (±1 SD shown by the grey area).

Power generation

Peak power generation was higher in the hips than in the knees ($p < 0.001$ for both legs) and slightly more power was generated in the trailing than in the leading leg (Figure 5). However, the difference in peak power generation between the legs was not statistically significant ($p = 0.43$ and $p = 0.97$ for the knees and hips, respectively). During the first part of the stride phase, the trailing hip absorbed power, as indicated by the negative values in Figure 5. Towards SFC, the trailing hip started to generate power up until MER. In the other joints, there was only a very small amount of power generation/absorption during the stride phase. The power generation in the trailing knee peaked slightly just before SFC and subsequently returned to approximately zero again. In the leading hip, there was a small positive peak just before SFC, followed by a considerable negative peak between SFC and MER and a (higher) positive peak again around BR. The power generation in the leading knee remained low until a small peak occurs around BR.

Discussion

The purpose of this study was to examine the energy flow through the lower extremities during a baseball pitch. The energy flow was examined by assessing both the transfer and generation of energy in the leading and trailing leg based on the joint power analysis of Robertson and Winter (1980).

Our findings show that there is a build-up in the amount of energy transfer over the joints. When inspecting the time courses of the power transfer, it can indeed be seen that

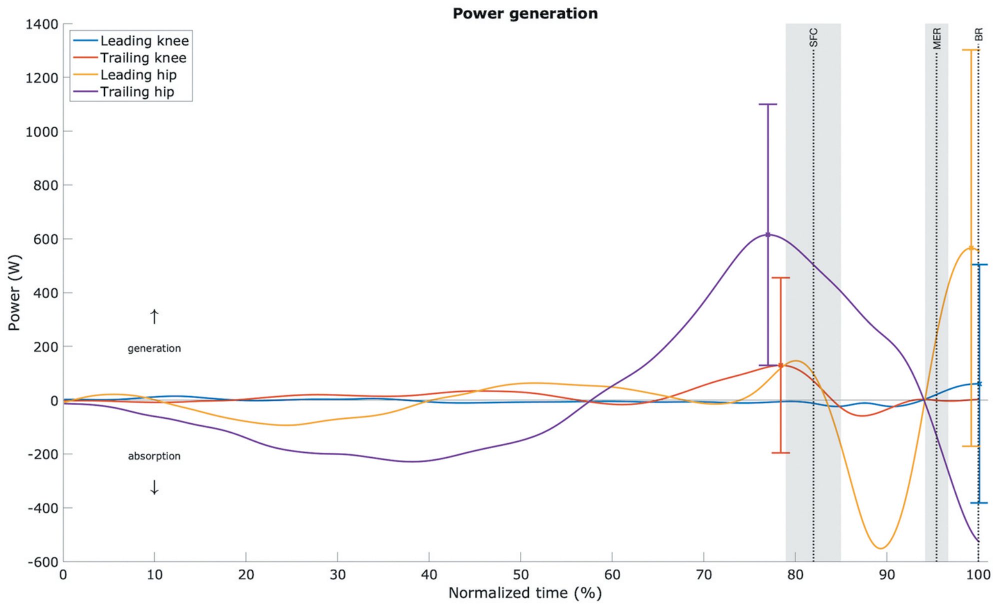


Figure 5. Mean normalised power generation time series for the knees and hips of the leading and trailing leg for all participants. The asterisks depict the estimated peaks of the mean power generation time series. The vertical dotted lines depict the mean timing of the events of SFC, MER, and BR (±1 SD shown by the grey area).

from the leading ankle upwards more energy is transferred through each subsequent joint. Furthermore, there is a clear distal-to-proximal order in the peak power transfer timing. This build-up in energy transfer magnitude together with the distal-to-proximal sequence imply that there is energy transfer up the kinetic chain in the leading leg, as was hypothesised, and supports the idea of a kinetic chain in the leading leg. However, we did not expect to find energy transfer in the leading leg before SFC. Our results show that the ankle, knee, and hip are mainly transferring energy up the kinetic chain before the foot has landed on the ground, indicating that the energy transfer in this leg is not (only) due to a stabilising function after SFC. In L5-S1, the power transfer (which only included the JFP and not the STP) peaks just after the foot has landed, indicating that the energy that is transferred up the leading leg during the stride phase is passed on to the thorax after SFC. These results are in line with the study of Winter & Robertson (1978) on the energy patterns in normal gait, who also found an upwards directed energy transfer in the leg pendulum during the second half of the swing phase (when approaching foot contact).

The trailing leg also transfers energy upwards (from distal to proximal) but energy does not flow through this trailing leg the way it flows through the leading leg. The trailing ankle, hip, and L5-S1 transfer energy upwards just before and just after SFC where the power transfers in the ankle and hip peak before the power transfer peaks in L5-S1. There is also a considerable amount of energy transfer down the trailing leg. In the knee, the power transfer is negative during almost the entire pitch and in the hip and L5-S1 the power transfer shows negative values for the main part of the stride phase. Furthermore, the peak power transfers in the trailing leg do not show a specific sequential order both in magnitude and timing. This indicates that the trailing leg does not contribute to the pitch by acting as a kinetic chain. However, the trailing leg might still be important for the energy flow as in another study it was found that the energy transfer by the trailing hip was an important contributor to the increase in mechanical energy of the pelvis segment (Kimura et al., 2020).

Overall, the trailing leg generates more energy than the leading leg. The observed energy generation is in accordance with our hypothesis that the trailing leg is the main driver of—at least the initial part of—the pitching motion and is also in line with the results of several other studies showing that pitchers should use their trailing leg to drive themselves towards home plate with maximal effort (Elliott et al., 1988; Howenstein et al., 2020; MacWilliams et al., 1998; Ryan & Torre, 1977). In that sense, the commonly used term 'trailing' might be misleading and we suggest using the term 'driving leg' instead. The peaks in trailing leg power generation occur around SFC and can therefore contribute to the energy flow to the ball. The leading leg also generates and absorbs a fair amount of energy, which was not expected since this leg has to minimise joint motions to form a stable base for the subsequent segment rotations. However, the energy generation is mostly negative during the arm-cocking phase when the leading leg has to form the stable base. This result is physiologically reasonable since the leading hip has to decelerate the body's centre of mass, and therefore absorb energy to create the stable base. This is reinforced by the decrease in the upward energy transfer, and even some downward energy transfer, through the leading hip during this phase in alignment with the results of Aguinaldo and Nicholson (2021). However, it seems important that the magnitude and duration of the energy absorption is minimised to preserve pitch performance. Therefore, future research should examine the role of this negative peak in relation to pitching performance. The positive peaks in the leading leg power generation occur around ball release, making it unlikely that this energy still contributes to ball speed. However, there is also a small peak in leading hip power generation just before SFC that is possibly contributing to ball speed.

The hips generate considerably more energy than the knees in both legs, meaning that the hips are more important for adding energy to the pitching motion. This is in accordance with the findings of Roach and Lieberman (2014) who revealed the hips to be the main energy generators for the acceleration of the trunk and distal arm segments. This is also in line with the study of Kimura et al. (2020), who found that the energy generation by the leading hip was important for increasing the mechanical energy of the pelvis around the superior-inferior axis. The higher magnitude of energy generation in the hips and the considerable magnitude of energy absorption in the leading hip underline the importance of ensuring strong hip and core musculature by employing strength training in order to improve pitch performance (Chaudhari et al., 2011).

Based on the current findings, it is suggested that the leading and trailing leg contribute in different ways to the pitching motion. The leading leg really acts as a kinetic chain with a distal-to-proximal energy transfer and the trailing leg acts as a driver by generating energy. These different actions are not easy to describe as a single kinetic chain. More likely, the legs form a special and separate component of the kinetic chain during a baseball pitch. Ultimately, the actions of both legs come together in the pelvis, where their contributions to the energy flow are combined. The resulting energy is funnelled through L5-S1, where the second, and more commonly discussed, open kinetic chain starts.

Considering the timing of peak power generation close to SFC, it is unlikely that the generated energy in the knees and hips is first transferred down the legs and subsequently upwards again. Instead, the energy generated in the leading and trailing leg around SFC is most probably added to the energy that is transferred upwards to the pelvis and subsequently to the trunk through L5-S1. Hence, it still remains unclear where the energy transferred up the leading (and trailing) leg comes from. Possibly, the energy is generated in the ankle joints. We were not able to evaluate this variable, so future studies should include this in order to clarify the role of the ankles in the energy flow through the lower extremities. Moreover, besides energy generated by muscle contractions, energy can also originate from a conversion of potential to kinetic energy. During the stride phase of the pitch, the body is lowered by stepping of the mound which converts potential into kinetic energy. It is possible that by using the leading leg as a sort of pendulum, the kinetic energy gained from the conversion is first used to increase the energy of the leading leg after which it is transferred up the kinetic chain. This theory would correspond with the timing of the energy transfer in the leading leg at the end of the stride phase, just before the pendulum hits the ground, and the leading leg has been able to gain a large amount kinetic energy. Furthermore, it would also be in accordance with the statements of House (1983), who advocated that a pitch should start with 'a controlled fall, not a violent drive' towards home plate. More research is needed to investigate the possible conversion of potential into kinetic energy (in the leading leg) during the stride phase and its role in the energy flow through the lower extremities.

The purpose of this study was to provide some initial insights into the energy flow through lower extremities. However, it is not without its limitations. Traditionally, bottom-up inverse dynamics are used to calculate the joint forces and torques in the lower extremities. However, during the stride phase the leading foot is not on the ground, meaning that no ground reaction force can be measured and the top-down approach has to be adopted. Furthermore, we did not include the segment torque powers in determining the energy transfer through the ankles and L5-S1. It is important to take this into account when interpreting the results of the current study. It is also important to notice that we found a considerable amount of variation in the energy flow curves. However, we do consider this to be a strength of this paper since it means that even in such a diverse group of pitchers we still found clear results in support of a kinetic chain in the lower extremities.

While this study delineated the energy flow through the lower extremities, future studies should also explore its association with pitching performance and injury risk by linking energy flow to ball speed and critical joint loads (Fleisig et al., 1995). This will help to further understand the function of energy flow during baseball pitching and more importantly, what specific energy flow measures are essential for pitching with maximal ball speed and minimal injury risk. Recently, Aguinaldo and Nicholson (2021) have initiated this next step and found that energy transfer through the trailing hip and energy generation by the leading hip were predictors of ball speed in collegiate baseball pitchers.

This study extends the 2-dimensional joint power analysis of Robertson and Winter (1980) to a 3-dimensional model and applies it to the lower extremities in pitching. While this allowed to analyse the separate energy transfer and generation in the lower extremities during a baseball pitch, the limitation of this approach is the assumption that joint torques are produced by single-joint muscles and only affect the adjacent segments, thereby not accounting for the energy transfer by bi-articular muscles between non-adjacent segments (Robertson & Winter, 1980). In the future, musculoskeletal models should be used to take the contributions of these muscles better into account. Moreover, caution is warranted when translating the current findings to baseball pitchers of other ages and skill levels since pitchers of different ages and skill levels often display differences in their mechanics (Fleisig et al., 1999).

Conclusions

The leading leg mainly transfers energy up the kinetic chain in a distal-to-proximal order just before stride foot contact. The trailing leg transfers energy as well but does not act as a kinetic chain. Instead, it accounts for most of the energy generation in the lower extremities, in particular at the hip. Hence, the legs contribute in different ways to the kinetic chain where the leading leg acts as an initial component of the kinetic chain and the trailing leg generates energy to drive the pitching motion. Both actions come together in the pelvis where they are combined and further passed on to the subsequent, and more commonly discussed, open kinetic chain starting at L5-S1. Future studies should examine where the energy that is transferred up the leading leg exactly originates and how the energy flow in the lower extremities contributes to pitching performance and injury risk.

Acknowledgement

The authors would like to thank the pitchers of Auburn High School Baseball for taking the time to participate in our study. They would also like to thank the Sports Medicine and Movement Lab for their support and assistance in data collection.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the NWO Domain Applied and Engineering Sciences (AES) under project number [R/003635]. This NWO-funded project, named Breaking the High Load—Bad Coordination Multiplier in Overhead Sports Injuries part of the Citius Altius Sanius perspective program (Project 7), is a cooperative effort between the Royal Dutch Baseball and Softball Federation (KNBSB), Royal Dutch Tennis Federation (KNLTB), Vrije Universiteit Amsterdam, Delft University of Technology, Milé Fysiotherapy, PitchPerfect and PLUX

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