



An Analysis of In Vivo Hip Kinematics in Elite Baseball Batters Using a Markerless Motion-Capture System

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Purpose: The aim of this study was to investigate the kinematics of the asymptomatic baseball batter's hips by comparing passive range of motion (PROM) and real-time active hip range of motion (AROM) and determine whether differences in ROM exist between lead and trail hips. **Methods:** Parameters of passive hip ROM were obtained using a goniometer and physical examination standards. Active hip ROM during batting swings was captured with the Dynamic Athletic Research Institute's markerless motion-capture system. **Results:** Twenty-nine elite-level baseball players were recruited for participation. Comparison of lead and trail hips showed no significant differences in PROM. Statistically significant differences in AROM were found between lead and trail legs with large effect sizes for flexion (mean difference [MD°], 11.22), extension (MD°, 30.30), abduction (MD°, 6.24), adduction (MD°, 18.63), external rotation (MD°, 14.87) and total arc of rotation (MD°, 17.17) ($P < .001$ for all). External rotation in the lead hip approached maximum passive endpoint during early phases of the swing, whereas trail hip extension reached maximum passive endpoint during follow-through. **Conclusion:** There is a significant difference in the AROM of the lead and trail hips during the batting swing, with active extension in the trail hip, active external rotation of the lead hip, and total arc of rotation of the lead hip nearing their respective passive endpoints and suggesting a potential for bony interaction in the hips of baseball batters. **Level of Evidence:** Level 3, Cross-Sectional Study.

There has been an alarming rise of injuries in the baseball athlete in recent years.¹⁻⁴ The risk of injury is multifactorial and is influenced by position, with pitchers at highest risk for upper extremity injuries at the professional level.^{3,5} Subsequently, a majority of

the kinematic literature is directed at restoring proper throwing mechanics, as well as injury risk in pitchers. With the concept of the "kinetic chain" gaining popularity, increased attention is now being paid to lower extremity risk factors for these upper extremity injuries.⁶ Flaws in any component of this chain can potentially increase injury risk in subsequent segments.⁷

Posner et al.³ delineated an increasing incidence of injury among professional baseball players with approximately 43% of these injuries involving the lower extremity, spine, or core, and most attributed to batting. The baseball swing is an explosive movement comprised of 6 operationally distinct phases: stance, stride, coiling, swing initiation, acceleration, and follow-through.⁸ The most dynamic movements in the swing occur during the acceleration phase where the lead hip experiences maximum rotation, but injury can occur during any one of the phases. Whether the athlete is a batter or pitcher, these injuries often cause significant missed playing time; therefore effective injury prevention and treatment is of utmost importance. Recent studies focused on baseball pitchers have

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Fig 1. Passive range of motion testing was completed with the subject resting supine on examination table. Range of motion was assessed using a goniometer with the hip positioned at the maximum range of motion.

examined passive and active hip range of motion (ROM) and side-to-side differences to help recognize the “at-risk” thrower; however, there have been no investigations evaluating the batter’s hips.⁹⁻¹²

Early biomechanical studies of the baseball swing were performed with 2-dimensional analyses of cinematographic film.¹³ Eventually, video techniques were developed, followed by the creation of computer-interfaced devices that could detect markers placed on the body. These marker-based systems have proven to be time-consuming and cumbersome, because they require the placement of several sensors onto the subject and calibration before testing. In addition, marker-based methods are susceptible to marker placement error; therefore reliability is low and operator dependent.¹⁴ Three-dimensional (3D) markerless motion-capture systems are a relatively new alternative to traditional sensor-based routines in analyzing human movement kinematics and gait.¹⁵ This technology has proven more consistent with repetitive testing and is being more frequently applied in the field of sports medicine for athletes’ rehabilitation and injury prevention.^{14,16-19}

The purpose of this study was to investigate the kinematics of the asymptomatic baseball batter’s hips by comparing passive range of motion (PROM) and real-time active hip range of motion (AROM) and

determine whether differences in ROM exist between lead and trail hips. It is hypothesized that active ROM during the batting swing would approach the maximal passive ROM, particularly for lead hip external rotation during the explosive acceleration phase of the swing.

Methods

After obtaining approval from the Institutional Review Board, 35 competitive baseball players were recruited from local high school varsity and college teams for participation in this cross-sectional study. Players reporting prior hip surgery or those unable to participate in standard, routine batting practice due to injury were excluded. Upon enrollment, patients were provided written informed consent and completed a questionnaire to obtain information on prior injury history, presence or characteristics of any current pain, prior treatments, experience level, batting handedness, and whether subjects participated in activities outside of baseball. All athletes reported that baseball was their primary sport.

Testing was performed in December 2019 at an indoor baseball performance center with passive ROM testing measured in an adjacent training room before kinematic testing. Players were selected randomly for testing and before initiation of the evaluation, each subject’s weight and height were entered into the system to establish baseline joint center locations of the elbow, shoulder, hip, knee, and ankle. Each subject was then evaluated using the Dynamic Athletic Research Institute (DARI) (Motion Platform version 3.2-Denali; Scientific Analytics Inc., Lincoln, NE) markerless motion-capture system. The accuracy of the markerless motion-capture system has been previously validated against other motion-capture systems.^{15,17,19,20}

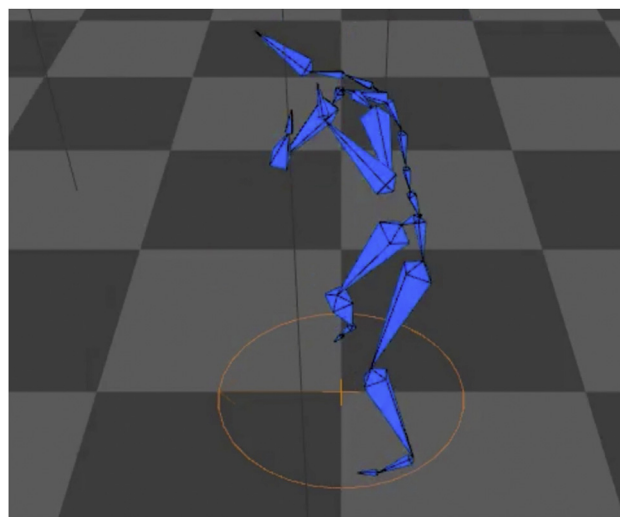


Fig 2. A full-body motion-capture skeleton was created from cloud voxels, which translate to a human’s volumetric silhouette that generates the parameters.



Fig 3. Examination area where kinematic testing was recorded via specifically oriented overhead cameras.

Passive ROM Testing

Passive ROM of each hip was measured using a large bubble goniometer with the pelvis secured to the examination table (Fig 1), consistent with other study methods.^{10,21,22} Flexion, extension, abduction, internal rotation with hip at 0° extension and 90° of flexion and external rotation with hip at 0° extension and 90° of

flexion were each assessed 3 times by 2 orthopaedic surgeons using a goniometer and with the hip positioned at the maximum range of motion.²¹ For hip flexion and extension, the goniometer arm was aligned with the diaphysis of the femur; for rotational measurements at the hip, the goniometer arm was aligned with the tibia. Hip rotation in flexion was assessed with the knees flexed at the end of the examination table and the pelvis remaining secured to the table. Total arc of rotation was calculated as the sum of internal and external rotation with 90° of hip flexion and 0° of hip flexion. Means and standard deviations of the recorded values were calculated.

Kinematic Testing

Once passive ROM testing was complete, the 3D DARI markerless motion-capture system was used to record kinematic data. Using full-body motion-capture acquisition (Fig 2), a computer-based software digitally recognized the study subject using 18 high-speed cameras (120 Hz) placed around a square-shaped enclosure. The DARI system has 12 cameras placed 2.6 m high, and 6 were placed on a lower level approximately 30 cm from the ground (Fig 3). Patients stood on a green screen where the DARI system created a 3D silhouette of each subject and a biometric skeleton was obtained (Fig 4). Data files were uploaded to a secure DARI Motion Platform where biomechanical analyses produced full-body kinematic results.

Participants went through their standard, routine game-day warm up including stretches, practice swings,



Fig 4. Subject in examination area during kinematic testing performing movements for DARI system to calibrate before swinging.

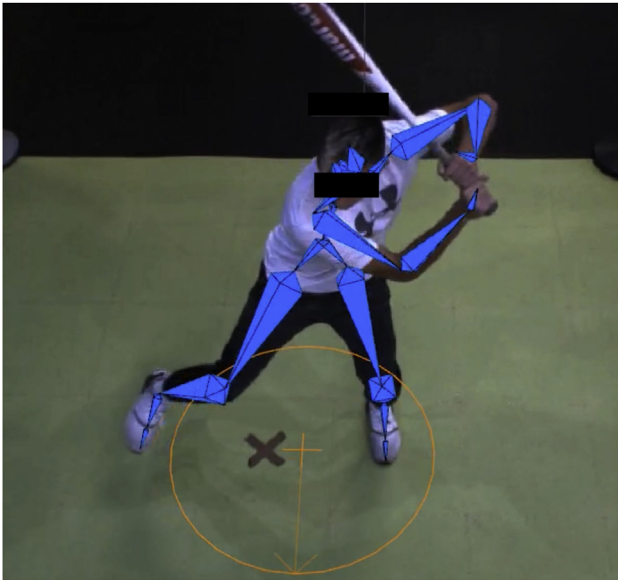


Fig 5. DARI system created a 3-dimensional silhouette of each subject and biometric skeleton during actual hitting motion.

and short sprints. Subjects were instructed to hit 10 baseballs off a standard batting tee adjusted to the subjects' preferred position and height. Lead and trail legs were determined by handedness during testing to avoid confusion in the case of a switch hitter. All participants used a regulation National Collegiate Athletic Association bat and the last 3 swings were analyzed (Fig 5). The collected kinematic data were saved and transmitted directly to the software. The compiled ROM data that were extracted from the software included maximal hip flexion, extension, adduction, abduction, internal rotation, and external rotation during the hitting motion. Total arc of rotational motion was calculated as the sum of internal and external rotation.

Statistical Analysis

Statistical analysis was performed with SPSS Version 22 (IBM, Armonk, NY). Means and standard deviations were calculated for measured passive ROM parameters and active ROM parameters recorded by DARI for the lead and trail hips of each subject. Comparisons between the lead and trail hips were performed using a 2-tailed paired *t*-test and presented with mean differences (MDs) and effect sizes (*d*). Data were then synchronized to examine variables as a function of time. This was used to plot range of motion data throughout the phases of the baseball swing. Effect sizes were categorized as either small (<0.2), medium (0.5), or large (>0.8).²³ Statistical significance was set with $P < .05$; however, because multiple statistical comparisons were performed, a Bonferroni correction was applied to the analyses of ROM.

Results

After applying eligibility criteria, 29 of the 35 players were included for testing. The mean age of the studied cohort was 18.1 ± 2.50 years with a mean height of 1.79 ± 4.64 m and weight of 81.2 ± 13.4 kg. Average body mass index among studied subjects was 25.6 ± 5.24 kg/m². A total of 18 players were right-handed batters, whereas the remaining 11 players were left-handed batters (Table 1).

Comparison of lead and trail hips between study subjects showed no significant differences in passive ROM (Table 2). On the other hand, kinematic data analyzing active ROM while batting found significant differences with large effect sizes between lead and trail legs for flexion, extension, abduction, adduction, external rotation, and total arc of rotation ($P < .001$ for all). A summary of the kinematic measurements captured by the DARI system for all 29 players is presented in Table 3. Figure 6 represents typical ranges seen for each hip motion recorded during the swinging motion. ROM data plotted over time was then used to examine hip motion during each phase of the baseball swing. Figures 7 and 8 show mean hip motion measurements as a function of time throughout the baseball swing.

Discussion

This descriptive study has reliably characterized normal hip kinematics in elite, asymptomatic high school and collegiate baseball players during the hitting motion by using a markerless motion-capture system. The results confirmed our hypothesis, showing that active extension in the trail hip, active external rotation of the lead hip, and total arc of rotation of the lead hip of baseball players approach their respective passive endpoints during the swinging motion. This is important because when an athlete's functional ROM approaches the physiological ROM defined by their bony hip morphology, risk for femoroacetabular abutment increases with potential for symptomatic hip labral injury. Compensatory motion through the lumbar spine, sacroiliac joints, pubic symphysis, core/trunk, and peri-hip musculature can often accommodate to meet the athlete's needs. However, the asymmetries

Table 1. Player Demographics

	n = 29
Age (mean, SD)	18.1 ± 2.50
Body mass index (mean, SD)	25.6 ± 5.24
Level of playing experience (n, %)	
High school	3 (10.3%)
College	26 (89.7%)
Hitting preference (n, %)	
Right-handed	18 (62.1%)
Left-handed	11 (37.9%)

SD, standard deviation.

Table 2. Passive ROM for Lead and Trail Hips For All Subjects: Mean Passive ROM (n = 29)

	Lead Hip	Trail Hip	P Value	Mean Difference	Cohen*
Flexion°	120.11 ± 6.76	119.01 ± 5.94	.324	1.103	0.173
Extension°	33.58 ± 5.86	34.33 ± 6.88	.420	1.137	0.113
IR in 0° of extension	28.83 ± 1.60	28.67 ± 2.41	.764	0.161	0.079
ER in 0° of extension	37.33 ± 2.45	37.03 ± 1.92	.608	0.299	0.136
Abduction	40.39 ± 5.51	39.22 ± 4.87	.322	1.172	0.225
IR in 90° of flexion	31.74 ± 4.58	31.43 ± 4.60	.686	0.310	0.068
ER in 90° of flexion	44.58 ± 4.03	43.98 ± 2.14	.352	0.598	0.185
Total arc of rotation in extension°	56.16 ± 2.59	55.70 ± 3.49	.540	0.460	0.150
Total arc of rotation in flexion°	66.31 ± 6.16	65.40 ± 5.81	.382	0.908	0.152

ER, external rotation; IR, internal rotation; ROM, range of motion.

*Small difference < 0.2, Medium 0.5, Large > 0.8.

caused by these compensatory mechanisms put increased strain on each individual link within the kinetic chain, and often these functional demands exceed the physiological limitation, thus leading to injury.

The phases of hitting have been previously described.²⁴ A hitter will start the swing with rotation of the arm, shoulder, and hip segments, while shifting weight toward the rear foot. This action can be considered the act of loading or coiling, in which the center of gravity of the body moves away from the ball and body weight is concentrated on the trail leg through slight flexion of the knee and hip.^{24,25} As the hitter transitions to the approach phase, the lead leg begins externally rotating, although the trail hip joint extends via eccentric contraction of the hip flexors and is abducted and externally rotated.⁸ Hitters approach maximum passive external rotation in the lead hip during this phase of hitting, immediately before contact with the baseball (Fig 7). Trail hip ROM then approaches maximum passive extension after contact during the swing, primarily during the follow-through phase (Fig 8). Functionally, the lead and trail legs have distinct roles and motion sequences in the baseball swing. The significant differences in maximal requisite active ROM parameters between the lead and trail legs reported in this study corroborate this concept. Throughout the entirety of the baseball swing, the hip segment allows the kinetic system to link the

musculature of the trunk and upper extremity. Excessive rotation of individual segments within the system may contribute to a reduction of muscular efficiency as well as produce a disruption in the sequencing of segments.

A loss in hip range of motion indicates a decrease in femoroacetabular capacity for movement, which can disrupt the kinetic chain of the baseball swing. Not only could this lead to suboptimal ball speeds and swing power by affecting the timing of muscular activation, but these adaptations could also add significant load to the hip and labrum, as well as the soft-tissue envelope including the hip capsule.⁸ Additionally, the pelvic torque required throughout the hitting motion can force the hips into maximum active external rotation in the lead hip that may potentially predispose the batter to premature hip abutment.²¹

Several studies have solidified the hips' role in the overhead athlete by showing that hip mechanics directly influence shoulder and elbow strain via the kinetic chain.^{8,22,26-28} Other studies further demonstrated a loss of hip ROM categorically by player position over the course of a single baseball season and associated it with injury.^{7,10,26,29-31} Our findings suggest there is an absence of reserve total arc of rotation of the lead hip, which may be a risk factor for the development of symptomatic FAI. Though the players in this study were asymptomatic, poor batting mechanics,

Table 3. Kinematic data for active ROM of lead and trail hips for all subjects: Mean Active ROM (n = 29)

	Lead Hip	Trail Hip	P Value	Mean Difference	Cohen*
Flexion°	37.53 ± 14.70	26.31 ± 16.70	<.001	11.22	1.01
Extension°	2.40 ± 15.23	32.69 ± 19.14	<.0001	30.30	2.47
Abduction°	19.56 ± 11.11	25.80 ± 7.34	0.032	6.24	0.94
Adduction°	30.65 ± 10.20	11.91 ± 9.92	<.0001	18.63	2.62
Internal rotation°	11.06 ± 9.54	8.76 ± 9.95	.378	2.30	0.33
External rotation°	43.58 ± 13.04	28.71 ± 12.64	<.0001	14.87	1.64
Total arc of rotation°	54.64 ± 15.47	37.47 ± 12.99	<.0001	17.17	1.70

ROM, range of motion.

*Small difference < 0.2, Medium 0.5, Large > 0.8.

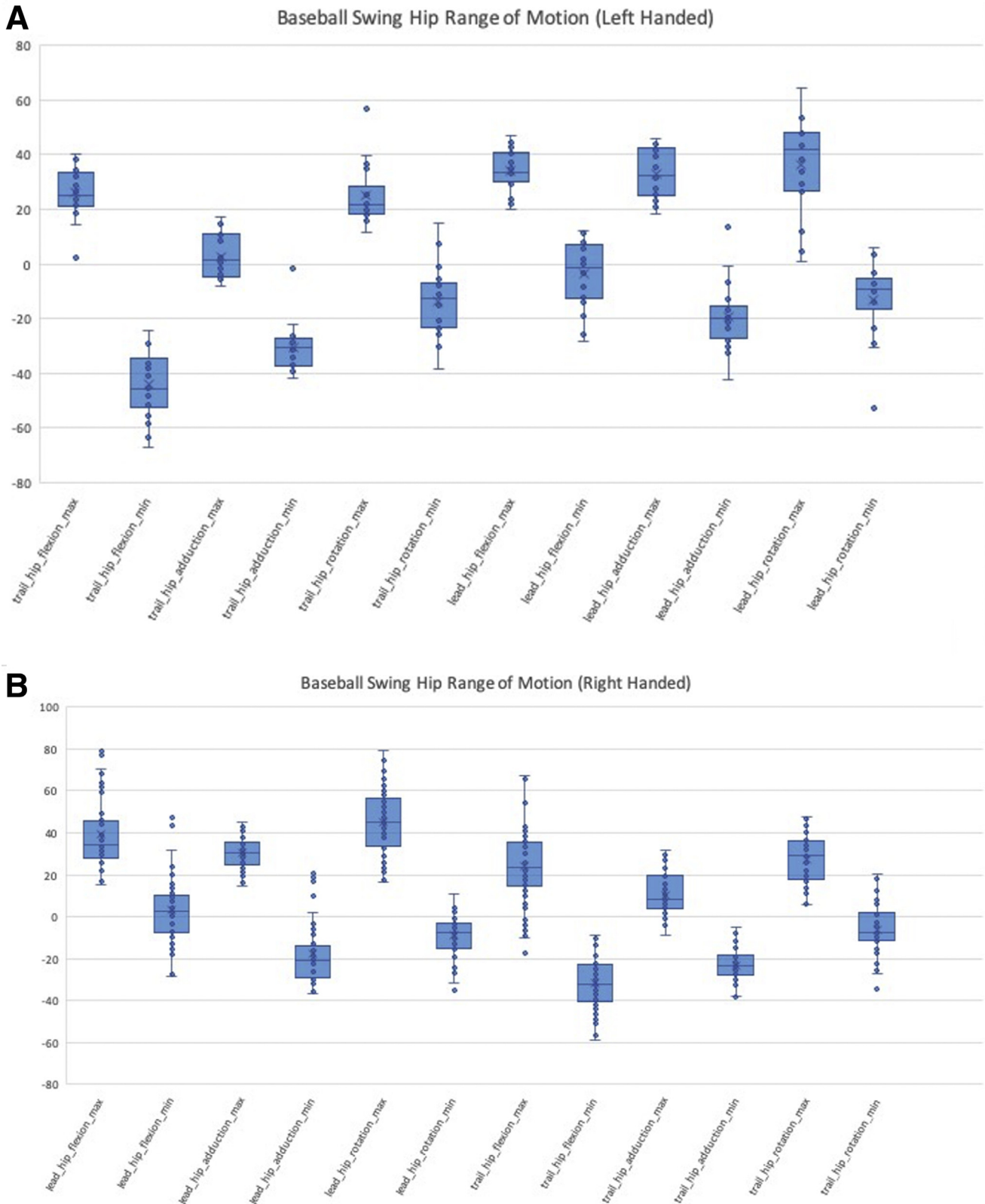


Fig 6. Box plot representing the kinematic data of the swinging motion of left-handed hitters (A) and right-handed hitters (B) as collected by the DARI markerless motion-capture system. Box boundaries and the horizontal lines and crosses therein represent interquartile ranges Q1-Q3, median measurements, and mean measurements, respectively. Whiskers above and below the boxes mark the ninetieth percentile and tenth percentile, respectively, and dots indicate data points.

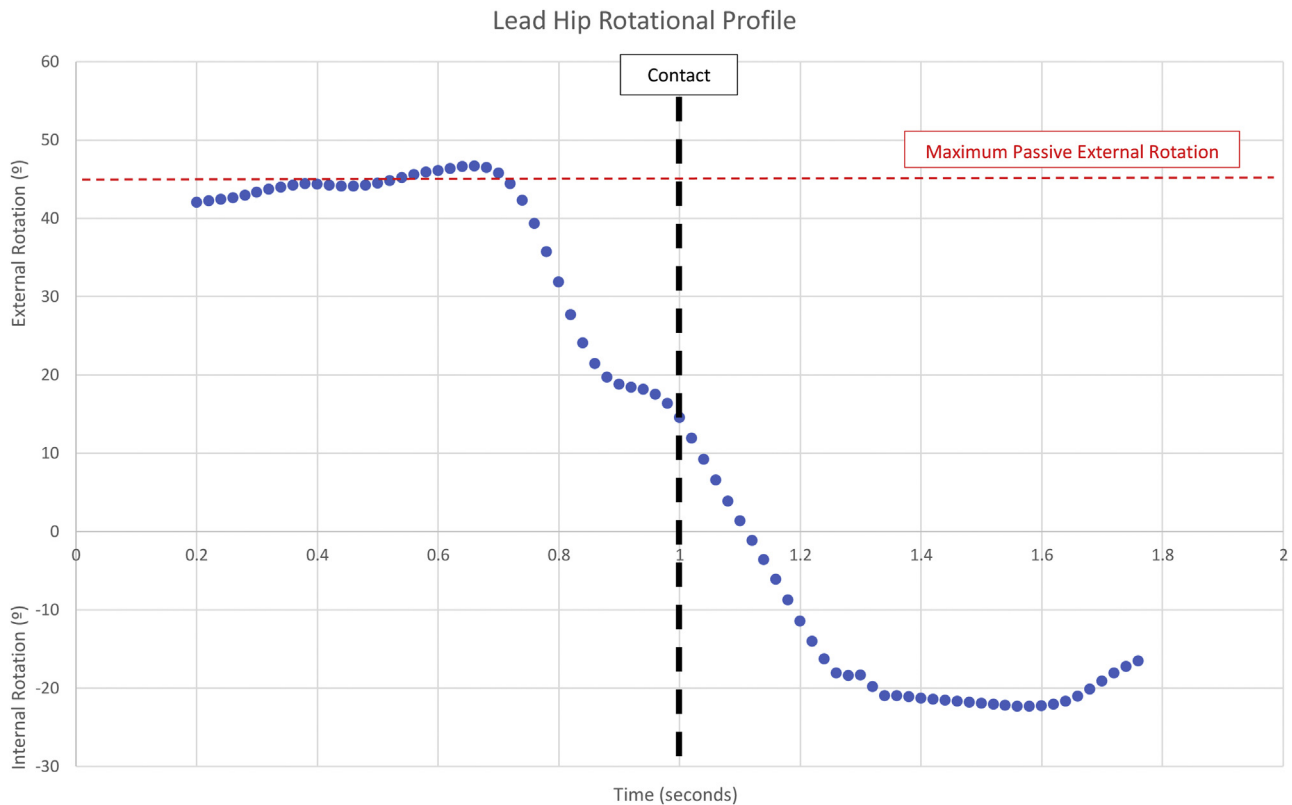


Fig 7. Lead hip rotation measured as a function of time throughout the baseball swing, where external rotation is positive, and internal rotation is negative. External rotation reaches maximum passive endpoint during early phases of baseball swing, particularly before contact. The vertical black dotted line represents the moment in time when contact between baseball bat and ball occurs. The horizontal red dotted line represents the mean passive external rotation.

limited range of motion, and muscular fatigue throughout the course of a game or season could manifest painful hip pathology or exacerbate symptoms caused by existing bony morphologies. These results are further strengthened by the application of markerless technology that is reproducible, accurate and operator independent.^{15,17,19,20} Although previous motion-analysis studies involving baseball athletes have been limited by marker-based capture systems, which have negatively affected sample size potential, the use of markerless technology enhanced our capability to screen more athletes in a short time. By reliably quantifying bilateral hip ROM in the hitting motion, our study provides a framework for clinicians and coaches to better understand the hip mechanics that characterize a sport-specific movement.

Although prior studies have focused heavily on throwing mechanics and the hips of pitchers, this study has uniquely investigated hip ROM during the baseball swing in vivo, successfully comparing passive to real-time active ROM with the DARI markerless motion-capture system. The purpose of this study was to provide a foundation for the biomechanical analysis of hitting and the preliminary synthesis of data for application to the rehabilitation and training of the hitting

athlete. The results indicate that there is a significant difference in the lead and trail hips of baseball players during active ROM while hitting with active external rotation in the lead hip nearing the passive endpoint. These findings support previous reports of pitchers reaching passive hip endpoints but also demonstrate an intra-player difference in lead and trail hip ROM and extend clinical implications to baseball hitters. This asymmetry between hips during the swing may lead to increased stress and dynamic overload of the pelvic girdle, consequently leading to injuries of the hip and groin. This study further defines normal kinematics in the hips of baseball players via passive and active ROM of the batting swing. In doing so, it creates a reference point with which future studies can more accurately describe hip pathology in the baseball population, such as how deficits in ROM can be associated with potential injury risk in hitters.

Limitations

There are limitations to the study. First, there are differences in how active and passive ROM values were recorded and compared. Passive hip rotation was measured by the clinicians in either 0° hip extension or 90° hip flexion. In contrast, maximal hip rotation

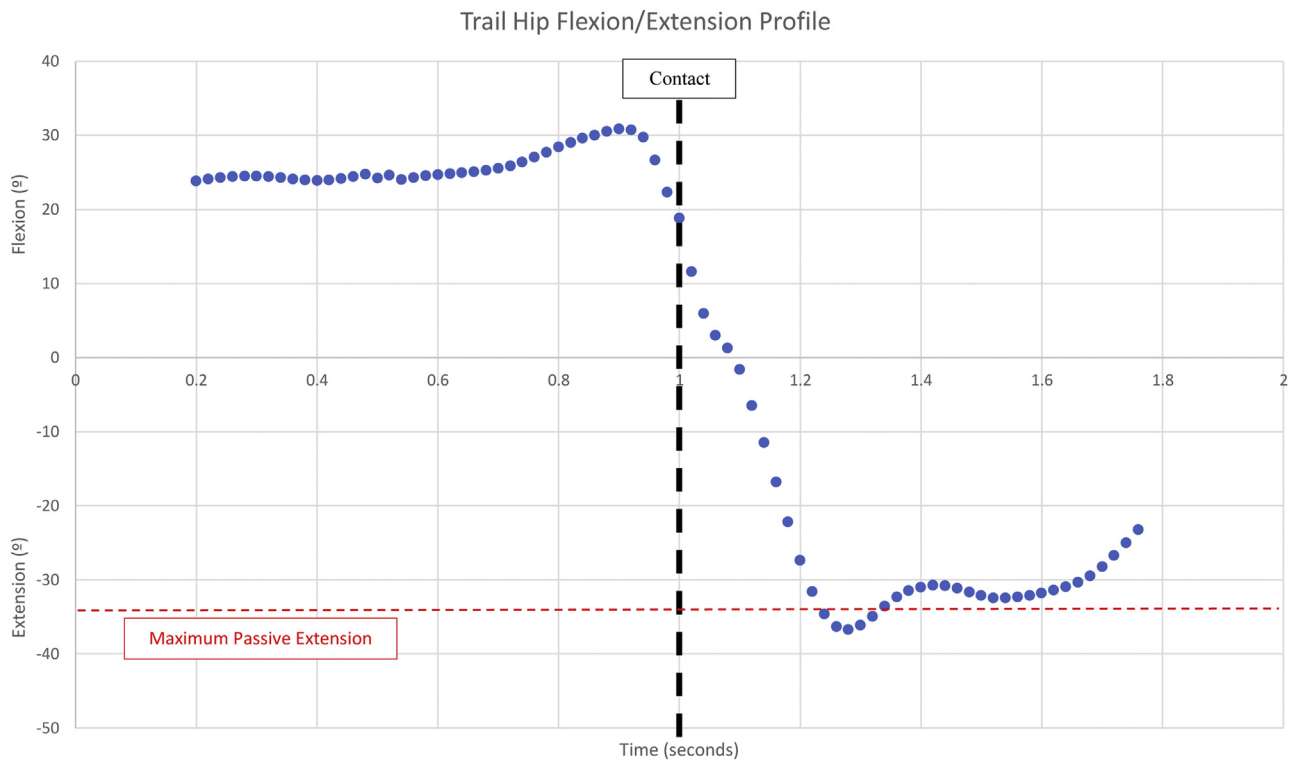


Fig 8. Trail hip flexion/extension measured as a function of time throughout the baseball swing, where flexion is positive, and extension is negative. Extension reaches maximum passive endpoint during later phases of baseball swing, particularly after contact. The vertical black dotted line represents the moment in time when contact between baseball bat and ball occurs. The horizontal red dotted line represents the mean passive extension.

measurements by the markerless motion-capture system could be made in any degree of hip extension or flexion during the swing. In addition, hip ROM measurements were only measured with the participant in the supine and seated position. The position in which hip internal and external rotation ROM is measured may influence both values, and some studies indicate that measuring in the prone position can eliminate confounding variables associated with measuring in the seated position.³² However, the passive ROM data can still be clinically useful because clinicians often measure ROM during physical examination in a similar manner. Another limitation of the study includes a lack of realism with swings being performed off of a tee. This eliminates variables such as the hitter's ability to recognize, react, and adjust to pitched the baseball, which could affect hip motion during the batter's swing.

Finally, lack of radiographic data is another drawback. Although femoroacetabular impingement is reportedly prevalent among elite athletes and a common cause of restricted hip motion, we are unable to confirm this correlation without radiographic imaging. Similarly, we are unable to determine whether any presence of FAI in the players tested affected the biomechanics of their swing motion, which could potentially confound some of the measurements collected. In addition, although

this study offers insight into the hip kinematics of the high-level baseball player, one should always remember that interplayer ROM measurements are not identical, and the use of multiple clinicians recording them can make random error possible on account of individual inconsistencies.

Conclusions

This study characterizes the normal hip ROM profile of the baseball batter. There is a significant difference in the AROM of the lead and trail hips during the batting swing, with active extension in the trail hip, active external rotation of the lead hip, and total arc of rotation of the lead hip nearing their respective passive endpoints and suggesting a potential for bony interaction in the hips of baseball batters.

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