Kinematics of Hitting in Youth Baseball: Implications for Skill Development

Authors

Nicole Bordelon[1], Anthony Fava[1], Kenzie B. Friesen[2], Ryan L. Crotin[3], Gretchen D. Oliver[1]

Affiliations

1 Kinesiology, Auburn University, Auburn, United States
2 Kinesiology, University of Calgary, Calgary, Alberta, Canada
3 Exercise and Nutrion Sciences, Louisiana Tech University, Ruston, United States

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Georg Thieme Verlag KG, Rüdigerstraße 14, 70469 Stuttgart, Germany

Correspondence

Prof. Gretchen D. Oliver
Auburn University
Kinesiology
301 Wire Rd
36849 Auburn
United States
Tel.: 8592004035, Fax: 8592004035
goliver@auburn.edu

ABSTRACT

This study compared lower extremity, trunk, and upper extremity kinematics between tee and front toss hitting in youth baseball athletes. Twenty youth baseball athletes (14.3 ± 2.9 yrs) performed three maximal effort swings off front toss and tee. Kinematic data were collected during the preparatory and acceleration phases. Lower extremity, trunk, and upper extremity kinematics were compared between tee and front toss hitting using 1-dimensional statistical parametric mapping (SPM). There was a significant difference in trunk kinematics between tee and front toss during the preparatory phase ($p = .001$); the trunk rotated more toward the back side when hitting off a tee compared to front toss ($p < 0.001$). There was also a significant difference in trunk kinematics between tee and front toss for 67 % of the acceleration phase; the trunk rotated more towards the back side from 0 to 67 % when hitting off the tee ($p < 0.001$). Significant differences were found in trunk kinematics between tee and front toss hitting in youth baseball players, where the trunk is less rotated toward the pitcher in the tee than in the front toss. Coaches utilize various training modalities to enhance hitting performance; however, differences in trunk kinematics should be considered between modalities when developing fundamental hitting techiques in youth baseball athletes.

Introduction

Baseball hitting is one of the most difficult skills in sports [1], since it requires precise coordination of the kinetic chain to achieve optimal batted ball velocity [1–3]. Two commonly used practice methods to improve offensive performance are tee and front-toss hitting. When hitting off of a stationary tee, the ball's preselected and static location makes it a constructive tool for isolating the development of mechanics without having to consider pitch variability [4]. For this reason, youth baseball athletes often invest more time hitting off a tee to master hitting mechanics before eventually progressing to front toss, which relies more on neuromuscular training and cognitive motor skills associated with reacting to pitch speeds, movement, and locations [5]. Compared to stationary tee hitting, front toss hitting may require a batter to adjust their timing and kinematics to account for pitch location and velocity variances [6, 7]. The pitch variability in a competitive environment requires the hitter to have sound coordination of the kinetic chain to achieve optimal contact and batted ball velocity [8, 9].

Although tee and front toss can address unique training goals, little is understood about differences in kinematic parameters between each hitting modality. Ae et al. [10] examined kinematic differences in the lower extremities between tee hitting and a machine pitched ball in a sample of collegiate baseball athletes. The findings showed decreased trunk rotation velocity and greater overall swing time in the pitched ball condition [10]. Another study by Chen et al. [7] compared collegiate baseball hitting mechanics across front toss, motor imagery, video projection, and virtual reality conditions. The results determined greater upper trunk rotation toward the back side when hitting a front tossed ball compared to hitting off a video projection and virtual reality conditions [7]. Lastly, a single softball hitting study examined the kinematic differences between tee and front toss hitting in collegiate athletes [6]. The findings indicated front-side knee flexion, trunk lateral flexion, and pelvis and trunk rotation differed between tee and front toss conditions at various events of the hitting motion [6]. Despite these findings in collegiate softball athletes, there is a gap in the literature investigating differences in mechanics between tee and front toss hitting in youth baseball athletes.

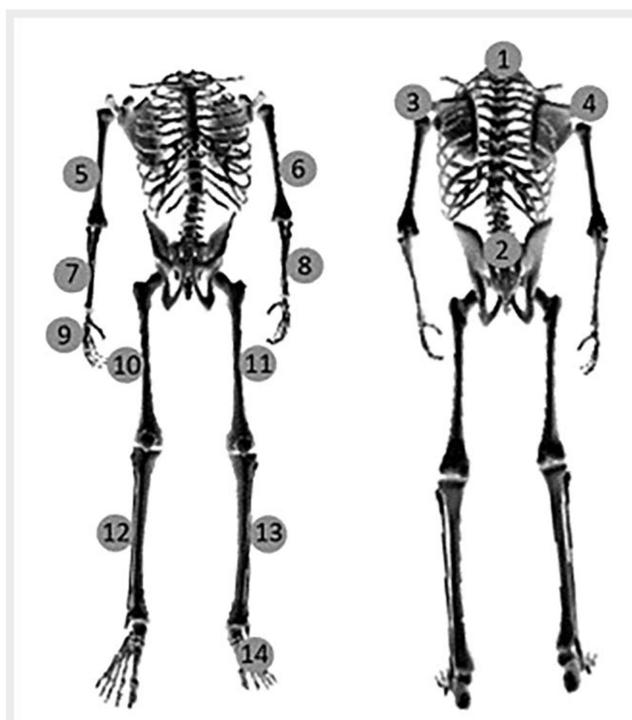
Prior baseball and softball hitting research suggests differences in kinematics across hitting modalities in collegiate athletes; however, it is unknown whether these differences exist in a youth athletes. A better understanding of the kinematic differences between each hitting drill would aid coaches in selecting the most appropriate method for their training goals. Thus, investigative work is necessary to understand and communicate altered hitting mechanics throughout the kinetic chain that may depend on hitting drill selection. Therefore, the purpose of the study was to compare lower extremity, trunk, and upper extremity kinematics between tee and front toss hitting in youth baseball athletes. Based on the aforementioned baseball and softball hitting studies [6, 7], it was hypothesized there would be differences in upper extremity, lower extremity, and trunk kinematics between tee and front toss hitting.

Materials and methods

Twenty male youth (9–17 years) baseball players (age: 14.3 ± 2.9 yrs, height: 169.5 ± 16.0 cm, weight: 69.0 ± 17.3 kg) who were active on a team roster and injury or surgery free for at least six months prior to visiting the lab participated. Thirteen participants were identified as 'high school' athletes (14–17 years), and seven of the thirteen high school players competed in travel leagues. Seven participants were identified as youth athletes (9–13 years), and all reported competing in travel leagues. The high school and youth athletes were combined for statistical analysis. On average, the participants played competitive baseball for 7.0 ± 2.9 years and indicated they were in-season for baseball 7.3 ± 2.5 months of the year. Participants were recruited to the laboratory through coaches, players, and/or family members expressing interest and reaching out to the laboratory to participate in biomechanical evaluations. Participants arrived for a single visit to the indoor laboratory in the appropriate athletic attire (loose-fitting t-shirt, athletic shorts, and preferred pitching tennis shoes). Prior to data collection, all testing procedures were thoroughly explained by the researcher, and written parental consent and participant assent were obtained. All testing procedures were approved by the University's Institutional Review Board.

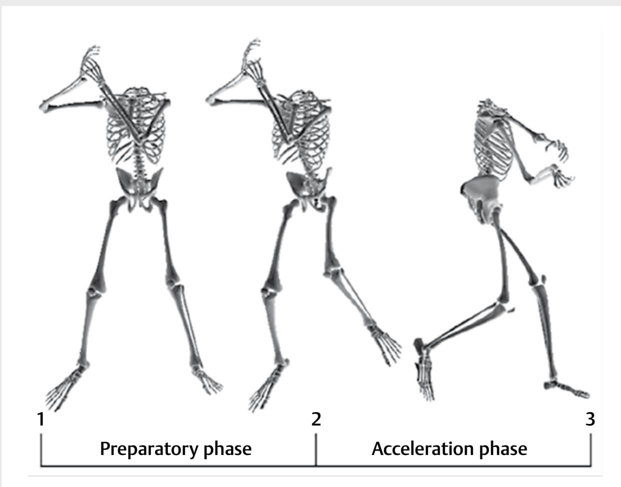
Kinematic and kinetic data were collected at 240 Hz with an electromagnetic tracking system (trakSTAR, Ascension Technologies Inc.; Burlington, VT, USA) synchronized with analysis software (The MotionMonitor XGen, Innovative Sports Training; Chicago, IL, USA) [11–16]. Fourteen electromagnetic sensors were attached to the participants using previously established standards (▶ **Fig. 1**) [11–17]. Sensors were placed on (1) dorsal aspect of the second metatarsal of the front-side foot (2–3), bilateral lateral aspect of the shank (4–5), bilateral lateral aspect of the thigh (6), sacrum between left and right posterior superior iliac spines, (7) posterior aspect of the trunk at first thoracic vertebrae spinous process (8–9), bilateral scapula on the flat broad portion of acromion (10–11), bilateral aspect of the humerus 1–2 cm proximal of the elbow (12–13), bilateral lateral aspect of the distal forearm, and (14) dorsal aspect of the back-side hand on the third metacarpal. A 15th moveable sensor was attached to a rigid stylus for digitizing bony landmarks to develop a linked-segment model in accordance with International Society of Biomechanics standards [18, 19]. Raw data regarding sensor position and orientation were independently filtered along each global axis using a fourth-order Butterworth filter with a cut-off frequency of 13.4 Hz [20, 21]. The world axis was represented with the positive Y-axis in the vertical direction. Anterior to the Y-axis and in the direction of movement was the positive X-axis. Orthogonal and to the right of X and Y was the positive Z-axis. Position and orientation of body segments were consistent with International Society of Biomechanics recommendations [18]. Euler angle decomposition sequence of ZX'Y" was used for trunk motion relative to the world while the YX'Y" sequence was used for shoulder motion relative to the trunk. Elbow motion was defined relative to the humerus using the Euler angle decomposition sequence of ZX'Y". Hip and knee motions were defined as distal segment relative to proximal segment using the Euler angle decomposition sequence of ZX'Y".

Following sensor attachment, participants were provided unlimited warm-up time to feel comfortable and ready to perform maximum effort swings [6]. Participants were also asked to use the same bat they use in a competition to prevent an unfamiliar bat from interfering with their hitting mechanics [6]. Participants performed three trials of maximal effort swings from a stationary tee followed by three maximal effort swings from a front toss with a pitcher located 9.14 m



▶ **Fig. 1** The placement of 14 electromagnetic sensors.

in front of home plate. Performing three maximal effort swings per condition is similar to methods from prior hitting studies [17, 22]. At least one minute of rest was allotted in between each swing trial. The tee was placed at a distance from the body to reflect a pitch in the middle of the strike zone and centered midway between the knee and hip [6]. Hitting trials were deemed successful if the result was a line drive, front toss location was over the middle of the strike zone, and the hitter verbally affirmed it was a 'good' swing [6]. A line drive was defined as the ball having a flat trajectory hitting the back net of the batting cage. These procedures mimic how a strike, tee placement, and a successful swing would be determined in a practical setting. Although reliability for these measures was not determined, visual identification of a strike, tee placement, and parameters for a successful swing are consistent with the methods used in tee and front-toss hitting research [6, 17, 21, 23, 24]. Verbal affirmation was required since swing mechanics can vary between athletes and temporal feel of the swing is related to successful hitting performance [25]. The participant was instructed to rest in between each maximum effort swing while the recorded trial was reviewed in The MotionMonitor XGen software and saved on the computer. Data for each kinematic variable were averaged across the three trials per modality three trials. Kinematic variables used for comparison included bilateral knee, hip, and elbow flexion as well as pelvis rotation, trunk rotation, trunk lateral flexion, trunk flexion, and pelvis to trunk separation. The front and back-side extremities were those closest to the pitcher and catcher, respectively.

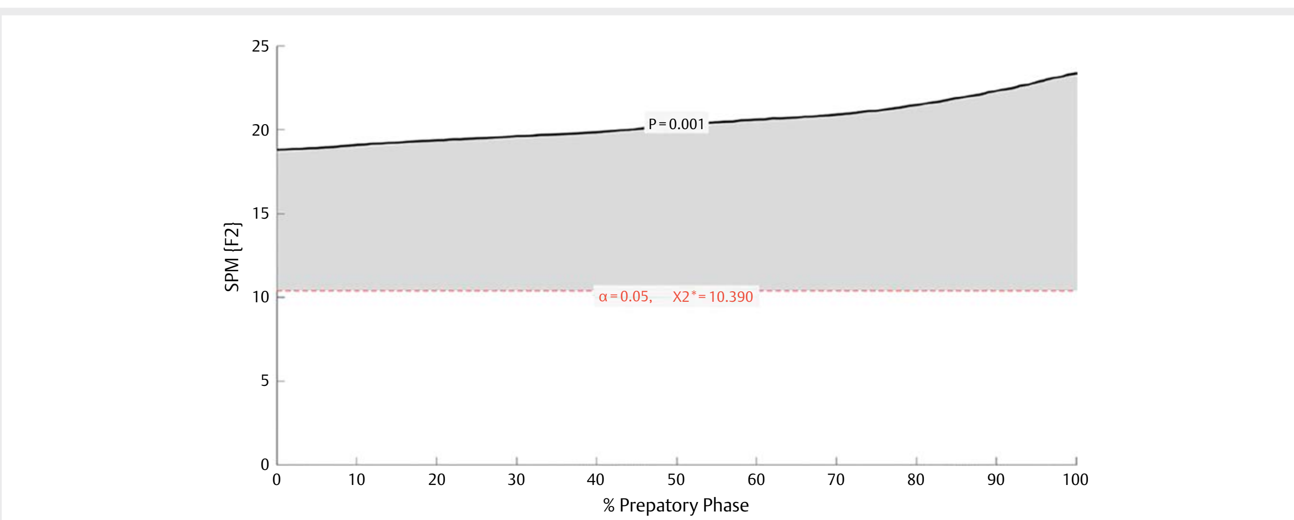


► **Fig. 2** Events of the swing and phases analyzed. (1) Start; initial displacement of pelvis towards the catcher; (2) Load; maximal displacement of pelvis towards the catcher; (3) Ball contact; maximal back hand angular velocity.

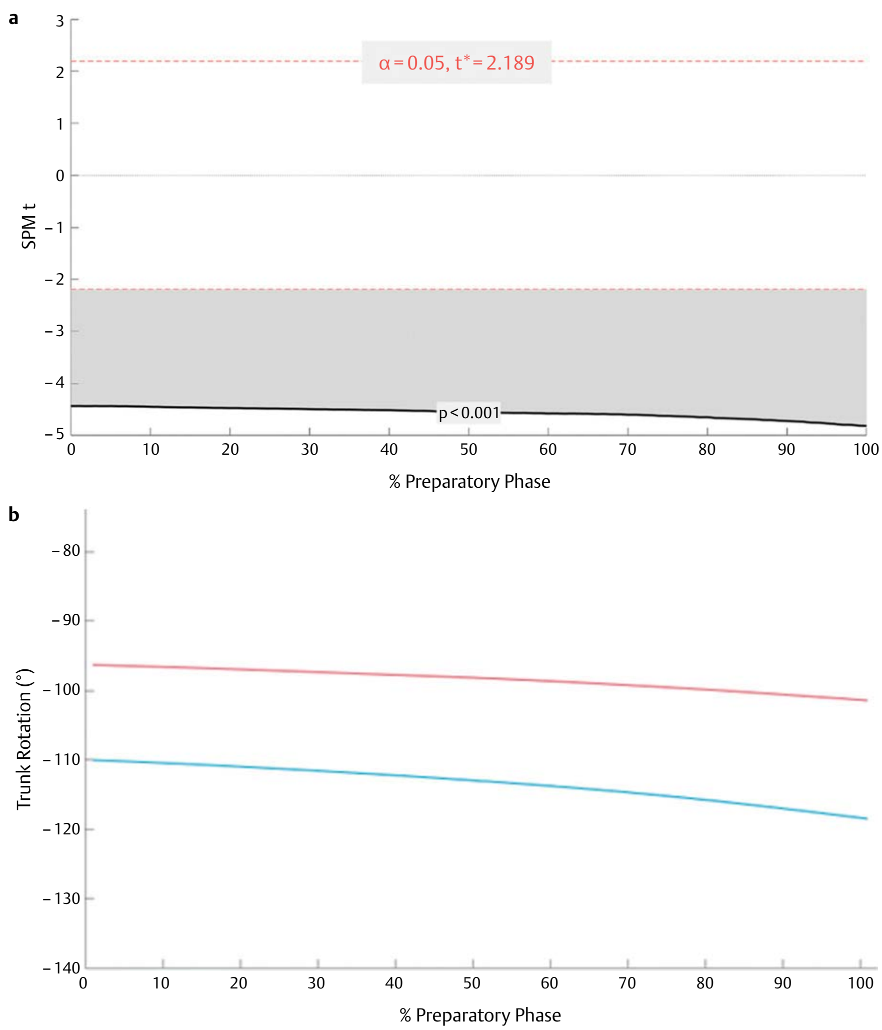
Prior to analysis, the baseball swing was separated into two phases: the preparatory phase and the acceleration phase (► **Fig. 2**). The preparatory phase was marked by two events: (1) start; the first 1 cm change of posterior displacement of the pelvis in the negative x-direction toward the catcher; (2) load; maximum posterior displacement of the pelvis in the negative x-direction toward the catcher. The second event also marked the start of the acceleration phase and ended with the third event of ball contact defined as one frame after maximal back hand angular velocity. The events of the swing were marked in each trial. Using a customized MATLAB (Mathworks) script, data between the start and end of both the preparatory and acceleration phases were extracted and normalized to 101 data points which represented 0–100 % of each phase of the hitting motion for each condition (tee and front toss).

Statistical Analysis

To conduct multiple comparisons across each phase of the swing, 1-dimensional statistical parametric mapping (SPM) multivariate analysis of variance (MANOVA) within-subjects testing were performed. Statistical parametric mapping is a novel approach to hitting research given its unique ability to examine mechanics across an entire phase rather than limiting analysis to a single time point. Initial use of within-model SPM{*F2*} MANOVAs enabled hypothesis testing at the multivariate level to be performed over time (0–100 %



► **Fig. 3** Trunk SPM MANOVA for the preparatory phase. The black line represents the SPM{*F2*} test statistic at each point in time throughout the preparatory phase; horizontal dashed lines represent the test statistic critical threshold; SPM = statistical parametric mapping.



▶ **Fig. 4** Trunk rotation (**a**) SPM t-test and (**b**) kinematic plots for the preparatory phase. The black line represents the SPM{t} test statistic at each point in time throughout the preparatory phase; horizontal dashed lines represent the test statistic critical threshold; SPM = statistical parametric mapping. (**b**) Comparison of trunk rotation between tee (blue line) and front toss (red line) conditions; −180° = facing catcher, 0° = facing pitcher.

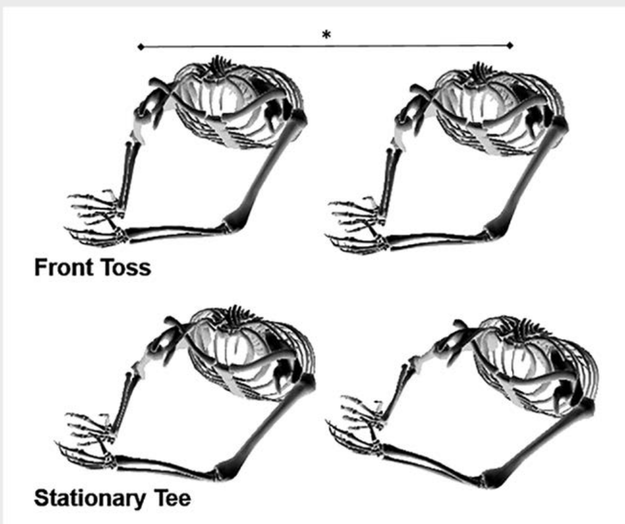
of each phase) [26]. For multivariate testing, kinematic variables were sorted by body segment/joint which resulted in the following kinematic variable groups: a) trunk; b) knee; c) hip; and d) elbow. Kinematic variables that comprised each group were as follows: a) trunk rotation, lateral flexion, flexion, and pelvis to trunk separation; b) knee (flexion for both front and back legs; c) hip (flexion for both front and back legs; and d) elbow (flexion for front and back arms). For every phase, 1-dimensional SPM MANOVAs compared the combined dependent kinematic variables of each variable group (a-d) and condition (tee and toss). A total of eight SPM{*F2*} MANOVA tests were performed in MATLAB 2020 A (Mathworks) using the open-source software package *spm1d* [27]. An alpha level of 0.05 denoted statistical significance. In the case of a significant MANOVA test, follow-up paired-samples t-tests were performed in MATLAB 2020 A (Mathworks) using SPM{*t*} tests for each kinematic variable associated with the significant MANOVA omnibus test. Post hoc testing using SPM{*t*} tests then permitted comparisons between tee and front toss conditions using continuous data (101 data points) for each kinematic variable [27–29]. To account for multiple comparisons when performing follow-up paired samples SPM{*t*} tests, a Sidàk stepdown correction was applied to each observed p-value [30].

Results

The average batted ball velocity for tee and front toss were 115.1 ± 21.2 km/h and 112.7 ± 20.8 km/h, respectively.

Preparatory Phase

The preparatory phase within-subjects SPM{*F*} MANOVA indicated a statistically significant difference in the combined dependent kinematic variables of the trunk between conditions expressed over 100 % of the preparatory phase (▶ **Fig. 3**). According to SPM{t} follow-up testing, differences in trunk rotation between hitting conditions were found for 100 % of the preparatory phase (p = 0.001) (▶ **Fig. 4**). SPM{*t*} revealed that trunk was more rotated toward the back side (catcher) throughout 100 % of the preparatory phase when hitting off the tee compared to the front toss condition (p < 0.001) (▶ **Fig. 4, 5**). No significant differences between tee and front toss conditions were determined for the remaining trunk variables (trunk flexion, trunk lateral flexion, and pelvis to trunk separation) throughout the preparatory phase. SPM*{F}* MANOVAs did not find any other statistically significant differences in the preparatory phase for the combined dependent variables of knee, hip, or elbow kinematics between tee and front toss conditions; therefore, follow-up SPM{*t*} tests were not performed.



▶ **Fig. 5** Trunk rotation of the preparatory phase for tee and toss conditions (mean trunk rotation at start and end of phase illustrated). **p* < 001; significant difference between tee and front toss conditions across 100 % of the preparatory phase. Hitting off the tee condition displayed significantly greater trunk rotation towards the backside.

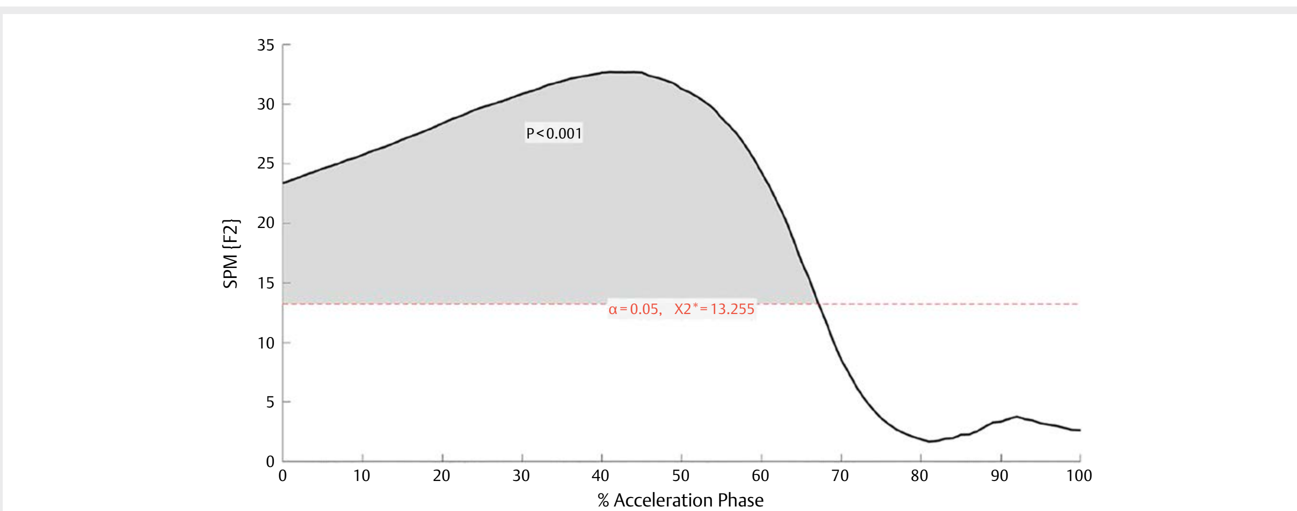
Acceleration Phase

The acceleration phase within-subjects SPM *{F2}* MANOVA further indicated a statistically significant difference in the combined dependent kinematic variables of the trunk between conditions expressed over 67 % of the acceleration phase (▶ **Fig. 6**). According to SPM{*t*} follow-up testing, differences in trunk rotation between hitting conditions were revealed from 0–67 % of the acceleration phase (p < 0.001). SPM{*t*} revealed the trunk was more rotated towards the back side (catcher) from 0 to 67 % of the acceleration phase when hitting off the tee compared to the front toss condition (p < 0.001) (▶ **Fig. 7, 8**). No significant differences between tee and front toss conditions were determined for the remaining trunk variables (trunk flexion, trunk lateral flexion, and pelvis to trunk separation) throughout the acceleration phase. SPM*{F}* MANOVAs did not show any other statistically significant differences in the acceleration phases for the combined dependent variables of knee, hip, or elbow kinematics between tee and front toss conditions; therefore, follow-up SPM{*t*} tests were not performed.

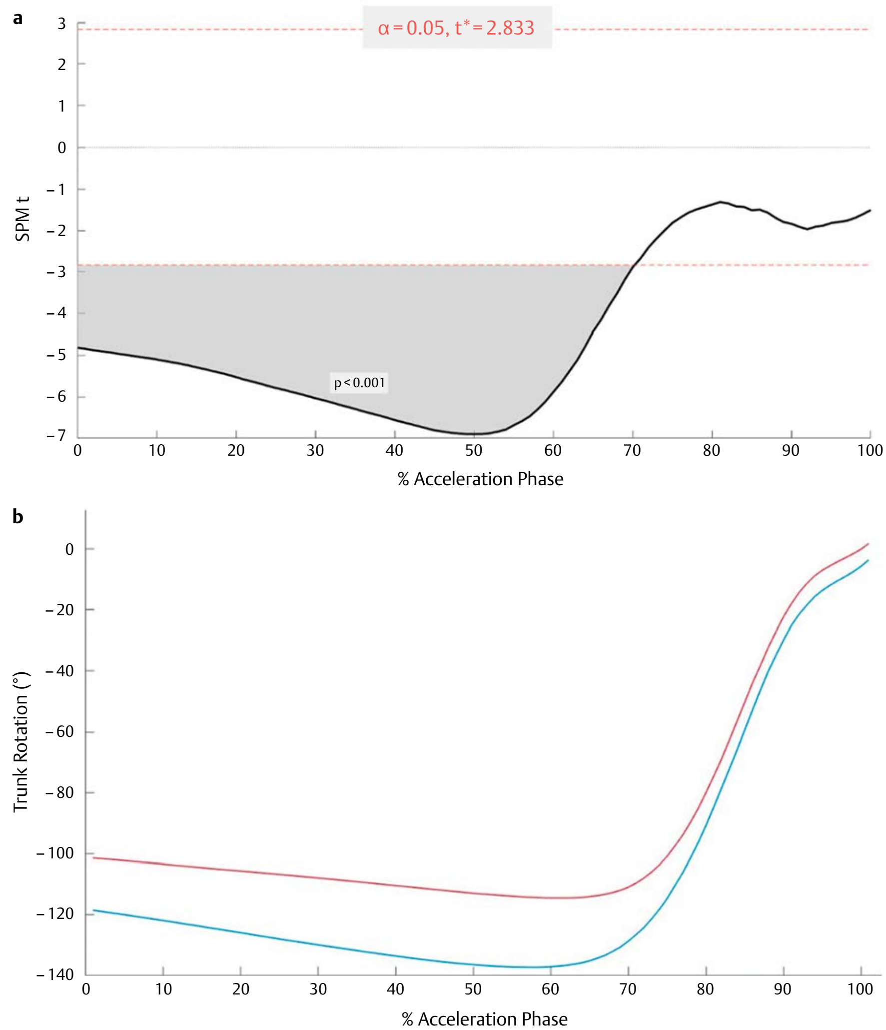
Discussion

The purpose of this study was to compare lower extremity, trunk, and upper extremity kinematics between tee and front toss hitting in youth baseball athletes. The results indicated there were significant differences in trunk rotation when hitting off a tee versus front toss. This partially confirmed the hypotheses, since other upper extremity, lower extremity, and trunk kinematics were not found to be significantly different. Specifically for the trunk, athletes demonstrated more rotation toward the back side (catcher) during the tee compared to the front toss condition during the preparatory and acceleration phases of the swing.

The findings suggest that youth baseball athletes modify trunk rotation depending on whether the ball is pitched or in a stationary position. Youth athletes may be more inclined to achieve greater trunk rotation towards the catcher during the tee position, since they can primarily focus on hitting the ball with a high exit velocity.



▶ **Fig. 6** Trunk SPM MANOVA for the acceleration phase. The black line represents the SPM{*F2*} test statistic at each point in time throughout the preparatory phase; horizontal dashed lines represent the test statistic critical threshold; SPM = statistical parametric mapping.

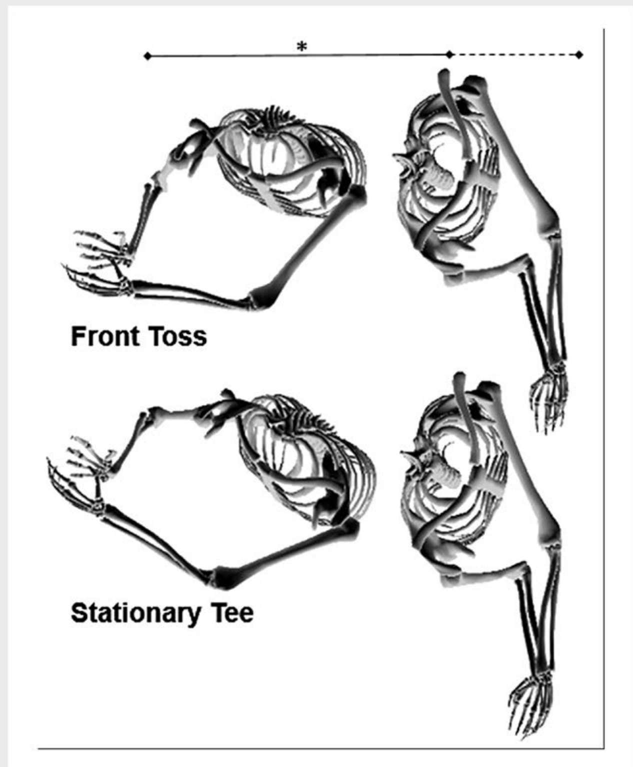


▶ **Fig. 7** Trunk rotation (**a**) SPM t-test and (**b**) kinematics plots for the acceleration phase. (**a**) SPM plot; black line represents the SPM{t} test statistic at each point in time throughout the preparatory phase; horizontal dashed lines represent the test statistic critical threshold; SPM = statistical parametric mapping. (**b**) Comparison of trunk rotation between tee (blue line) and front toss (red line) conditions; − 180 ° = facing catcher, 0 ° = facing pitcher.

Conversely, youth athletes may be less inclined to achieve the same degree of counter rotation towards the catcher during the front toss condition, since they must multi-task to attain a visual of the incoming ball, tracking its speed and location, and control their movement to achieve optimal contact.

The current study's findings contrast the collegiate softball hitting study by Washington et al. that reported greater trunk rotation toward the back side for the front toss compared to the tee condition [6]. However, the discrepancy is likely attributed to analyzing different competition levels, since prior research has shown that mechanics vary between youth and elite athletes [31]. In addition, the current study performed an SPM analysis that examined kinematics over the entire preparation and acceleration phases, while Washington et al. examined trunk rotation at single events during the swing [6].

A prior study by Chen et al. [7] compared collegiate baseball hitting mechanics across various modalities (front toss, motor imagery, video projection, and virtual reality). Athletes achieved greater upper trunk rotation toward the back side when hitting a front tossed ball compared to when athletes attempted to swing and hit a ball during video projection and virtual reality conditions [7]. The front tossed ball was the condition in which the ball was delivered at a slower speed, while the video projection and virtual reality conditions were delivered at faster speeds. Therefore, the current study and the study by Chen et al. [7] illustrate a pattern of decreasing trunk rotation toward the back side when the ball is pitched at increased speeds. Modifying trunk rotation may account for the timing needs of the batter to quickly transition from linear displacement during the preparation and early acceleration phases to a high



▶ **Fig. 8** Trunk rotation of the acceleration phase for tee and toss conditions (mean trunk rotation at start and end of phase illustrated). $^{*}p<001$; significant difference between tee and front toss conditions from the start to 67 % of the preparatory phase. Hitting off the stationary tee condition displayed significantly greater trunk rotation towards the backside.

rotation velocity of the trunk and shoulders during the remaining acceleration phase [32].

In the context of youth baseball athletes, the current study indicated that hitting a tossed ball produced less trunk rotation towards the backside. Therefore, variations in trunk mechanics across the preparation and acceleration phases of the swing may limit the transferability of hitting off a tee to more game-like contexts. Awareness of these differences in trunk kinematics between hitting modalities can help coaches structure a hitting program unique to an athlete's needs. While hitting off a stationary tee can still be advantageous for youth hitters needing to isolate their focus on improving specific swing mechanics, coaches should ensure athletes are maintaining consistent mechanics across all hitting modalities that transfer to live pitching. Coaches seeking additional assistance to help youth control their trunk rotation across various hitting modalities may also seek out resistance training since strength and power exercises have been shown to aid performance in hitting sport-specific tasks [33, 34]. For example, medicine ball rotation throws performed specific to the ranges of motion of the swing may be used to enhance power development while aiding drill transferability of hitting a ball at increased speeds [33].

Lastly, it is important to note the degree of trunk rotation is a single factor in a series of precise movements contributing to the baseball swing. It is also important to consider factors such as the timing of rotation and rotational velocities when seeking to improve performance. Rather than directly comparing the relationship between the degree of trunk rotation and hitting performance, studies have primarily compared trunk mechanics across competition levels. Studies have demonstrated differences in the degree of trunk rotation across competition levels as well as higher trunk rotation velocities in more skilled athletes [4, 35]. The results suggest coaches should consider both the degree of trunk rotation and rotational velocity when training hitters. Additional research should compare the degree of trunk rotation as well as trunk rotational velocities between front toss and tee hitting modalities in youth baseball athletes.

Important study limitations should be noted. The first is pitch location was deemed in the center of the strike zone through visual observation only. Although some variability can be expected between strike zone and tee placement based on visual observation, the current study's other criteria for a recorded trial served as delimitations. Additionally, the tee was placed in the middle of the strike zone and centered midway between the knee and hip for all participants. Other study criteria including line drive hit trials only and verbal affirmation from the participants helped to ensure tee placement was considered close to the middle of the strike zone. Second, a standard bat was not used across participants, yet this was similar to prior softball hitting methodologies that allowed participants to use the bat they were comfortable swinging in a competition setting to make the practice experience more game-like and individualized [6, 17]. Results may have been confounded by a bat weight or length that was unaccustomed to the athlete for which altered mechanics could have been a result of a change in mass-moment of inertia in the swing, or potentially insufficient or greater strength relative to bat weight and length. Lastly, the age range can be considered a limitation of the study; however, all athletes reported playing on travel league teams, which is considered a higher level of competition than recreational leagues.

In conclusion, there was a significant difference in trunk kinematics between tee and front toss hitting conditions in youth baseball athletes. Specifically, there was greater trunk rotation toward the back side in the tee condition throughout the preparatory phase and 67 % of the acceleration phase compared to the front toss condition. There were no other significant differences between tee and front toss conditions for all other lower extremity, upper extremity, and trunk kinematics across the preparatory and acceleration phases of the swing. Though it is understood that coaches utilize various training modalities when seeking to enhance hitting performance, the potential differences in trunk mechanics should be considered when seeking to develop fundamental hitting techniques in youth baseball athletes. Hitting off a stationary tee can still be advantageous for youth hitters needing to isolate their focus on improving specific swing mechanics; however, coaches should ensure athletes maintain consistent mechanics across all hitting modalities to ensure skill sets translate to live pitching.

Lastly, future studies should consider utilizing statistical parametric mapping (SPM) as a novel method for investigating hitting mechanics. This method has gained popularity in baseball [36] and softball [37, 38] pitching research given its unique ability to examine mechanics across an entire phase rather than limiting analysis to a single time point. As a growing number of studies seek to further understand hitting mechanics, SPM can provide a more comprehensive interpretation of mechanics throughout the phases of the swing. Considering that the current study only compared mechanics between tee and front toss hitting conditions, additional research is needed to compare mechanics during live hitting to improve the transferability of findings to a competitive environment.

Conflict of Interest

The authors declare that they have no conflict of interest.

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