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Schaefer, Andrew; Ferdinands, Rene E. D.; O'Dwyer, Nicholas; Edwards, Suzi. "A biomechanical comparison of conventional classifications of bowling action-types in junior fast bowlers", Published in *Journal of Sports Sciences* Vol. 38, Issue 10, p. 1085-1095 (2020).

Available from: http://dx.doi.org/10.1080/02640414.2020.1741972

This is an Accepted Manuscript of an article published by Taylor & Francis in Traffic Injury Prevention on 10/03/2020, available online: https://www-tandfonline-com/doi/full/10.1080/02640414.2020.1741972

Accessed from: http://hdl.handle.net/1959.13/1421347

ABSTRACT

Fast bowling is categorised into four action types: side-on, front-on, semi-open and mixed; however, little biomechanical comparison exists between action types in junior fast bowlers. This study investigated whether there are significant differences between action-type mechanics in junior fast bowlers. Three-dimensional kinematic and kinetic analyses were completed on 60 junior male fast bowlers bowling a five-over spell. Mixed-design factorial analyses of variance were used to test for differences between action-type groups across the phases of the bowling action. One kinetic difference was observed between groups, with a higher vertical ground reaction force loading rate during the front-foot contact phase in mixed and front-on compared to semi-open bowlers; no other significant group differences in joint loading occurred. Significant kinematic differences were observed between the front-on, semi-open and mixed action types during the front-foot contact phase for the elbow and trunk. Significant kinematic differences were also present for the ankle, T12-L1, elbow, trunk and pelvis during the back-foot phase. Overall, most differences in action types for junior fast bowlers occurred during the back-foot contact phase, particularly trunk rotation and T12-L1 joint angles/ranges of motion, where after similar movement patterns were utilized across groups during the front-foot contact phase.

Key Terms: ***Cricket, fast bowling, biomechanics, kinematics, action-types***

INTRODUCTION

Fast bowling actions are typically categorised into four action-types: side-on, front-on, semi-open and mixed. These categories are typically based on two-dimensional "alignment angles" calculated in the transverse plane. The common alignment angles used are the shoulder alignment angle (angle calculated using the shoulder joint centres) and the pelvis alignment angle (angle calculated using the pelvis joint centres). From these alignment angles, shoulder counter-rotation (shoulder alignment angle at back-foot contact minus the minimum shoulder alignment angle from back foot contact to front-foot contact) and shoulder-pelvis separation angles (angle calculated as the difference between the shoulder alignment angle and the pelvis alignment angle) can be calculated (Ferdinands, et al., 2010).

The side-on action can be characterised by the shoulders being positioned more parallel to the wicket (the prepared strip of ground between two sets of stumps) leading to a restricted shoulder alignment angle ($<25°$) and shoulder counter-rotation ($<30°$) (Bartlett, et al., 1996; Ferdinands, et al., 2010). This action is also thought to be associated with the lowest rate of lumbar spine injury (Elliott and Khangure, 2002). However, only 15% of junior and 22% of senior fast bowlers use this action (Burnett, Elliott, & Marshall, 1995; Ferdinands, et al., 2010).

The front-on action displays an increased shoulder alignment angle ($>50°$) that is more perpendicular to the wicket but exhibits restricted counter-rotation ($<30°$), resulting in the bowlers shoulders being 'front-on' to the batsman at back-foot contact (Bartlett, et al., 1996; Ferdinands, et al., 2010). As for the side-on action, the front-on action-type is considered to have a lower lumbar spine injury risk (Elliott, 2000). This action has a varying frequency distribution (0-33%) among junior and senior fast bowlers (Burnett, et al., 1995; Portus, et al., 2004).

The semi-open action is an intermediate classification group between the side-on and front-on actions, and is classified when the participant displays a shoulder alignment angle between 25-50° and shoulder counter-rotation <30° (Ferdinands, et al., 2010). This action type has been associated with lower injury risk and to be present in 18% of senior fast bowlers who have been classified as using this action (Ferdinands, et al., 2010; Portus, et al., 2004).

The mixed action is characterised by the trunk beginning in a front-on position, before moving towards a more side-on position, thereby resulting in excessive shoulder counter-rotation (Elliott, 2000; Ferdinands, et al., 2010; Portus, et al., 2004). Threshold values of shoulder counter-rotation used to define the mixed bowling action has varied between previous studies; with threshold values of 20° used by Elliott (2000), 30° by Ranson, et al. (2008) and 40° by Foster, et al. (1989). The threshold of shoulder counter-rotation appears dependent on studies determining a new demarcation point based-on non-injured and injured groups of bowlers. The mixed action appears to place fast bowlers at the highest risk of injury and is the most common bowling action, varying from 44% to 80% in junior and senior fast bowlers (Burnett, et al., 1995; Elliott and Khangure, 2002; Ferdinands, et al., 2010; Portus, et al., 2004). The mixed bowling action could also be detrimental to performance with a decrease in bowling accuracy seen in this action-type in longer bowling spells (Portus, et al., 2000).

Despite junior fast bowlers being at high risk of developing injury, particularly in the lumbar spine (Dennis, Finch, & Farhart, 2005; Elliott and Khangure, 2002), few studies have investigated both the kinematic and kinetic differences between the types of bowling actions. Burnett, et al. (1995) and Portus, et al. (2000) found increases in shoulder counter-rotation in front-on bowlers during 12-over (junior) and 8-over (adult) spells respectively, yet the small samples (n=9 and n=14, respectively) pose the question of the reliability of these results. In contrast, a recent study by Schaefer, et al. (2018) of 25 junior fast bowlers (semi-open: n=10, mixed: n=9, front-on: n=5, side-on: n=1) found no substantial changes during a 10-over spell in mean values or variability of a comprehensive set of bowling variables, yet they did not compare differences in bowling actions. While, Ranson, et al. (2008) found no significant kinematic differences in lower trunk extension, contralateral side-flexion or ipsilateral rotation between mixed and non-mixed bowling actions in 50 senior fast bowlers (23±4 yr).

In summary, researchers have previously defined various fast bowling action-type classifications, but it has not been established whether key kinematic or kinetic thresholds significantly differentiate between the bowling action-types. In the few studies that have attempted such an analysis, the statistical power has been relatively low with the researchers restricted to a small sample size. The purpose of the current study was to compare the three-dimensional (3D) differences between known fast bowling action-type classifications in a larger cohort of junior fast bowlers.

METHODS

Participants

Sixty junior male fast bowlers (mean age=14.6±1.4 yr, height=1.76±0.1 m, mass=64.5±11.9 kg) were recruited from local district and zone level representative teams within New South Wales, across three cohorts. Participants were aged between 12-18 years, free of injury (including back pain) at the time of testing and classed as a fast bowler by the director of coaching for their district. Written informed consent was obtained from each participant and his parent/guardian prior to data collection and all methods were approved by the institution’s Human Research Ethics Committee.

Experimental Protocol

The participants' anthropometric dimensions (height; body mass; anteroposterior depth at the level of the greater trochanter and xiphod process; largest anteroposterior depth for the thoracic region) were measured prior to passive reflective markers being placed on the participants (Schaefer, et al., 2018). A standardised warm-up of balance and postural stability exercises was performed (Bird and Stuart, 2012), followed by six warm-up deliveries in order to familiarise the participants to the laboratory environment. A five-over spell of bowling consisting of good length deliveries was then performed, at a self-selected competition pace. Pre-delivery approach speed was measured by two infrared timing gates (Speed Light, Swift Sports Equipment, Lismore, Australia; or Smart Speed, Fusion Sport, Summer Park, Australia), and a non-bowling period of approximately 5 minutes was completed between each over (Schaefer, et al., 2018).

Whole-body 3D motions of the participants were recorded across two seasons (a separate cohort per season) using a motion capture system (500 Hz; 12 to 15 Oqus 300+ (Season 1) or Oqus 700+ (Season 2) cameras, Qualisys AB, Göteborg, Sweden). 3D ground reaction forces (GRFs) were measured using two multichannel force platforms (2,000 Hz; Type 9281CA and 9281EA, Kistler, Winterthur, Switzerland). The force platforms were embedded in the floor and connected to control units (Type 5233A and Type 5606, Kistler, Winterthur, Switzerland). The force platforms and run-up track were either covered with a 20mm polyurethane athletic track surface (Season 1) or an uncovered concrete surface (Season 2).

Data Analysis

All six balls from each of the five-overs (30 trials) were selected for analyses in Visual3D software (v6, C-Motion, Germantown, MD). Raw kinematic, GRF, moment and centre of pressure data were low-pass filtered with the same cut-off frequency (Butterworth digital, 4th-order zero-phase with f_c=18 Hz) before the calculation of individual joint kinematics and net internal joint moments and forces during the bowling action. An 18 Hz cut-off frequency for both the raw kinematic and force data was determined by initially performing a residual analysis of the raw kinematic data (Winter, 2009), adhering to the recommendations of Bisseling and Hof (2006) and Kristianslund, Krosshaug, & van den Bogert (2012). A customised LabView program (v2014, National Instruments Corporation, Austin, TX, USA) calculated the peak magnitudes and loading rates of the GRFs on the raw GRF data that was low-pass filtered at 50 Hz (Butterworth digital, 4th-order zero-phase), a method previously utilised in fast bowling literature (Crewe, et al., 2013).

To model each participant, segments were based on the passive reflective marker set placed on the participant (Schaefer, et al., 2018). Segment masses of the foot, shank, thigh, upper-arm, forearm, hand and head segments were defined according to Zatsiorsky, Seluyanov, & Chugunova (1990); whereas the pelvis, lumbar and trunk were defined according to Pearsall, Reid, & Livingston (1996). Geometric primitives were used to model the inertial properties of each segment (Hanavan, 1964), defining the pelvis, lumbar region and trunk as cylinders (Seay, Selbie, & Hamill, 2008); the foot, shank, thigh (Ford, Myer, & Hewett, 2007), upper-arm, and forearm as a frusta of a right cone; the hand as a sphere; and the head as an elliptical cylinder.

The following temporal events (and statistical factor) of the bowling action were defined automatically using Visual3D software and confirmed by visual inspection: back-foot initial foot-ground contact (BIC), front-foot initial foot-ground contact (FIC), the time of the peak vertical GRF (F_V), bowling upper-arm horizontal backwards (AH), ball-release (BR), bowling upper-arm vertically downwards (AV) (Schaefer, et al., 2018). It should be noted that BIC was defined as the maximum posterior acceleration relative to the laboratory coordinate system of the back-foot fifth metatarsal marker (Schaefer, et al., 2018), whereas FIC was defined at the time when the vertical GRF exceeded 10 N. The back-foot contact phase was defined from BIC to FIC, whereas the front-foot contact phase was defined from FIC to AV. All anatomical terms in the current study were defined with respect to right-handed bowlers.

To calculate the outcome variables of kinematics and kinetics, a Cartesian local coordinate system sign convention was utilised and defined as:

- x-axis = mediolateral axis
- y-axis = anterior-posterior axis
- z-axis = superior-inferior axis

An *x,y,z* Cardan sequence of rotation was used to express the 3D angles and net internal joint moments for the ankle, knee, hip, L5-S1 (lumbar segment relative to the pelvis segment), T12-L1 (trunk segment relative to the lumbar segment), elbow (*y*-axis cross-talk, or abduction/adduction, not reported), wrist (*z*-axis cross-talk, or rotation, not reported), as well as 3D angles for the trunk-pelvis (trunk segment relative to the pelvis segment), trunk (trunk segment relative to the laboratory coordinate system) and pelvis (pelvis segment relative to the laboratory coordinate system). Anticlockwise trunk axial rotation was defined as positive relative to the global transverse plane. Similarly, trunk-pelvis rotation was calculated as a separation angle with anticlockwise trunk axial rotation defined as positive. A *z,y,z* Cardan sequence of rotation was used for the shoulder joint angles. The 3D range of motion (ROM) were calculated as the difference between peak maximum and minimum joint angles for L5-S1 and T12-L1 during the phases of BIC-FIC and FIC-BR.

The outcome variables of two-dimensional alignment angles were calculated in the transverse plane according to the protocol used by Ferdinands et al. (2010). Pelvis and shoulder alignment (relative to the laboratory coordinate system) and shoulder-pelvis separation angle were calculated at the time of BIC and FIC. In addition, shoulder and pelvis counter-rotation were calculated as shoulder and pelvis alignment angle at BIC minus peak shoulder and pelvis alignment angles, respectively. Utilising the alignment angles, each participant's fast bowling action was classified according to the four primary classifications of Ferdinands, et al. (2010) via shoulder counter-rotation only. The primary action types are also a factor for statistical analysis.

Net internal joint forces and moments were estimated via inverse dynamics and peak GRFs variables were calculated between FIC-AV for all joints from the ankle to the T12-L1 intervertebral joint space. Kinetic variables were only computed during the front-foot contact phase as the small force platform size (600 x 400 mm) allowed only one-foot contact phase to be measured using the two force platforms. For any trial in which the front-foot missed or only partially contacted the force platforms, the kinetic variables were excluded from the statistical analysis (Unsuccessful trials: cohort 1=15.8±15.0%, cohort 2=13.7±15.6%, cohort 3=24.9±15.4%). Joint forces were normalised to body weight (relative BW) and peak net internal joint moments were normalised to the participant's body mass multiplied by height (relative BM x height).

The mean ball speed was calculated by taking the average velocity over 5 frames after ball release.

Statistical Analysis

Means were calculated for all kinematic (3D angles, 2D alignment angles, ROMs) and kinetic (forces, moments and joint forces) variables across all 30 trials to achieve this study's aim of accurately representing the characteristics of each action-type, with mean and standard error of the sample mean (SE) reported. To justify the utilisation of the means of all 30 trials, coefficient of variation and variance ratios were conducted, with the fast bowling action showing high levels of repeatability. These outcome variables were then analysed in a series of mixed-design factorial analyses of variance (ANOVAs) used to determine significant changes ($P<0.05$) in the means across action-types using Statistica (v.10, StatSoft Inc., Tulsa, OK, USA). Outcome variables were split into the following categories for the primary test of the effect of the action-types: angles, alignments, ROM, moments, and GRFs. Three factors (event*angles*actions) were used for the analyses of:

- 3D joint angles (N=22),
- trunk-pelvis angles (N=3),
- trunk angles (N=3) and
- pelvis angles (N=3).

The events encompassed the six critical time points of the bowling action: BIC, FIC, FV, AH, BR and AV. Different events were compared depending on the angles involved during the fast bowling action. As the lower limbs are not in contact with the ground during all the events, the back-foot lower limb angles (ankle, knee and hip) were compared across BIC and FIC, while the front-foot lower limb angles (ankle, knee and hip) were compared across FIC, FV, AH, BR and AV. Also, L5-S1, T12-L1, trunk-pelvis, trunk and pelvis joint angles were compared statistically across all six events of the fast bowling action. There were two factors for analyses of:

- peak GRFs (impulses*actions; forces*actions; timing*actions),
- joint forces (joints*actions),
- joint moments (moments*actions)
- 2D alignment angles (align*actions),

- anthropometrics (anthro*actions)
- approach speed (speed*actions) and
- L5-S1 and T12-L1 ROM (ROM*actions).

There was one factor (actions) for analyses of the measures of bowling speed and the vertical GRF loading rate. When significant effects were found, Tukey *post-hoc* tests were conducted to identify their precise locus. To report the effect sizes of the interactions of the repeated measures ANOVAs partial eta squared were employed. Effects sizes (η_p^2) were defined as trivial (<0.0099), small (0.0099-0.0588), moderate (0.0588-0.1379), and large (>0.1379) sizes (Richardson, 2011).

Factorial ANOVAs allow the researcher to evaluate the pooled effect of two or more experimental variables when used simultaneously. The greater the number of relevant sources of variance that are measured (e.g., event, angles and actions here), the smaller the variance due to experimental error (Winer, 1962). When multiple dependent variables require assessing, factorial analyses allow for the control of experiment-wise error, ensuring that tests on individual variables are carried out only where significant effects are identified. It is important to note that while significant effects were expected for factors such as event and angles, it was only significant interactions between action types and these other factors that were of relevance to the question of differences between action types. Hence, significant effects for event and angles were ignored and only their interaction with action-types are reported.

The data were first checked to ensure that they satisfied the assumptions of normality of distribution and sphericity. When these assumptions were violated, multivariate ANOVAs were used. One participant was excluded from analysis because he released the ball between BIC and FIC, an action substantially different to the traditional action in which the bowler releases the ball after FIC, potentially confounding the results.

RESULTS

General Bowling Characteristics

The distribution of bowling actions within the 60 participants is outlined in Table 1, with the side-on action removed from statistical analysis due to the low sample size (n=2). There was no significant main effect of actions on anthropometrics/approach speed ($F_{2,51}$=0.59, P=0.56, η_p^2=0.0226), nor any significant interaction of anthro*actions ($F_{6,153}$=0.38, P=0.89, η_p^2=0.0147). No significant differences were observed for the main effect of actions ($F_{2,54}$=0.14, P=0.87, η_p^2=0.0052) or between speed*actions for mean ball speed ($F_{2,54}$=0.14, P=0.87, η_p^2=0.0052).

****Table 1 near here****

Kinematics

The results of the mixed-design factorial ANOVAs of the kinematic data is in Table 2. For the statistically significant interactions, *post-hoc* analyses revealed several significant differences between action types. Significant differences between the front-on and semi-open action types included: greater bowling-arm elbow pronation (BIC) and trunk clockwise rotation (BIC and BR) for the semi-open action-type, whereas greater trunk anticlockwise rotation and shoulder alignment (BIC and peak) were displayed for the front-on action-type. For the significant differences between the front-on and mixed action types, the mixed action had greater bowling-arm elbow pronation (BIC), trunk clockwise rotation (BR), T12-L1 rotational ROM (BIC-FIC) and shoulder counter-rotation; but the front-on action displayed greater trunk anticlockwise rotation (AV). Finally, the mixed action exhibited greater back-foot ankle inversion (FIC), T12-

L1 clockwise rotation (BIC), T12-L1 rotational ROM (BIC-FIC), bowling-arm elbow pronation (FIC and FV), trunk-pelvis anticlockwise rotation (BIC), shoulder alignment (BIC), shoulder counter-rotation and shoulder-pelvis separation (BIC) compared to the semi-open action; but the semi-open action had greater trunk clockwise rotation (BIC). The specific outcomes of the *post-hoc* analyses can be found in Table 3. Means (±SE) for all kinematic pertinent to the analysis of the fast bowling action, including 3D lower limb angles (Appendix 1), L5-S1 and T12-L1 kinematics (Appendix 2), bowling-arm angles (Appendix 3), trunk and pelvis angles (Appendix 4) and alignment angles (Appendix 5).

****Tables 2 & 3 near here****

Kinetics

The outcomes from the mixed-design factorial ANOVA of the kinetic data can be found in Table 4. Following *post-hoc* analysis, one significant difference was present between the groups. A significantly lower vertical loading rate (LR-F_{V1}) was observed for semi-open (285±27.2 BW·s^{-1}) compared to front-on (399.3±30 BW·s^{-1}; P<0.05) and mixed (356.9±22.4 BW·s^{-1}; P<005) actions during front-foot contact phase. Means (±SE) of L5-S1 and T12-L1 joint forces are in Appendix 6.

****Table 4 near here****

DISCUSSION

This study is the first to investigate if differences in bowling kinematics and kinetics exist between action types. A significantly higher shoulder counter-rotation was observed in the mixed (49±1°) compared to the non-mixed bowling actions (front-on 35±2°; semi-open 28±2°). The 26 bowlers with a mixed action displayed excessive shoulder counter-rotation with 16 between 40-50º (61%), seven between 51-60º (27%) and three greater than 60º (12%). Shoulder counter-rotation has been previously linked with lumbar injury risk and performance (Elliott, 2000; Portus, et al., 2000), however, a consensus has not been reached on a threshold of shoulder counter-rotation that leads to an increased risk of lumbar injury or decreased performance. This study indicates however that bowlers with a mixed action are most likely at risk if the link between the amount of shoulder counter-rotation and lumbar injury is deemed to be true. To establish if this notion is supported, further investigation is required using a longitudinal study design.

The percentage of bowlers classified for the action-types in this current study compared to previously reported data was lower for side-on (3% v 15-22%) from (Burnett, et al., 1995; Ferdinands, et al., 2010), higher for semi-open action (30% v 18%) from (Ferdinands, et al., 2010; Portus, et al., 2004), and similar for the front-on (23% v 0-33%) from (Burnett, et al., 1995; Portus, et al., 2004) and mixed action-types (43% v 44-80%) from (Burnett, et al., 1995; Elliott and Khangure, 2002). The difference in frequency distribution between the side-on and semi-open actions could be due to differing thresholds of shoulder counter-rotation used to classify both action-types.

Shoulder-pelvis separation angle was found to be significantly different between action-types. Increased shoulder-pelvis separation angle at BIC of the mixed action (26°) compared to semi-open (10°) was seen in this study, potentially placing the lower back under stress, as increased separation angle has been related to soft tissue injury (Portus, et al., 2004). Unfortunately, this study was unable to investigate the effects of increased shoulder-pelvis separation angles on lumbar loading as one of the limitations of this study was that back-foot GRFs were not collected. This should be an area of focus for future research. Furthermore, shoulder-pelvis separation angle (at any time point) was not found to have an influence on ball speed since no significant differences in ball speed were observed between action types. Portus, et al. (2004) has suggested previously that a more positive shoulder-pelvis angle occurring closer to ball-release results in greater ball speed, however, this was not observed in the current study. This between-study difference may be due to the statistical methodology employed in which the current study factorial analysis based on grouping the cohort by action type, rather than individual correlations of Portus, et al. (2004), which would be recommended for future research.

Lumbar spine and trunk movement is of importance during fast bowling (Stuelcken, Ferdinands, & Sinclair, 2010). Mixed action bowlers displayed greater T12-L1 ROM (36±3°) compared to front-on (27±4°) and semi-open bowlers (25±3°) during the back-foot contact phase. These differences in T12-L1 motion are likely related to the greater amount of trunk rotation away from the bowling-arm of the mixed compared to the non-mixed actions, leading to greater T12-L1 movement. Also, the trunk in the semi-open action was in a more rotated position away from the bowling-arm (-50±2°) than both the front-on (-31±3°) and mixed actions (-27±2°), likely due to the shoulders being more rotated away from the bowling-arm at the point of BIC. However, by the time of ball-release the trunk in the front-on action is rotated more towards the bowling-arm (-12.2±4.3°) compared to the semi-open and mixed actions (-25.9±3.8° and -30.5±3.2°, respectively). The differences seen here in T12-L1 ROM and trunk kinematics, particularly in the mixed bowling action, indicate that most of the motion around the lumbar region occurs during the back-foot contact phase. Yet, without the aid of T12-L1 joint kinetics during the back-foot contact phase, it is unclear whether high levels of T12-L1 joint motion at BIC is influential on lumbar spine loading between different action-types.

The action-types differ in their spinal kinematics during back-foot contact that may translate to differences in front-leg and rear-leg mechanics during the delivery stride. It has been shown previously that rear thigh velocity makes a significant contribution to rear-leg drive and bowling wrist speed (Greene, et al., 2014). However, in this study the only difference found was an increase in ankle inversion in mixed bowlers (8±2°) compared to semi-open bowlers (3±2°), this may contribute to greater rear-leg push-off for mixed bowlers. Research has not previously reported whether front-leg kinematics differ between bowling action-types. Neither has a consensus been reached within the literature on whether knee joint angular kinematics is associated with ball speed or injury risk (Olivier, et al., 2015; Portus, et al., 2004; Worthington, King, & Ranson, 2013a). No differences in front-leg joint angles across actions were seen here, suggesting that junior fast bowlers adopt similar front-leg kinematic strategies despite employing different trunk mechanics according to their fast bowling action-type.

Little is known of the differences in bowling arm technique due to action-type, with only delayed shoulder circumduction shown to increase ball speed (Worthington, King, & Ranson, 2013b). Differences in elbow pronation were observed between the action-types, specifically at BIC for front-on (79.2°) compared to mixed (115.3°) and semi-open (111.1°), at FIC for mixed (85.3°) and semi-open (49.5°), and again at FV for mixed and semi-open bowlers (75.4° & 43.9°, respectively). The differences in elbow pronation are possibly related to pre-release strategies positioning the ball for performance outcomes such as increased in- or out-swing.

This study was the first known study to apply a whole-body kinetics analysis from the ankle to T12-L1, related to fast bowling action-types. One kinetic between-group difference during the front-foot contact phase was observed, with a decrease in vertical GRF loading rate for semi-open bowlers (285±27 BW·s^{-1}) compared to front-on (399±30 BW·s^{-1}) and mixed bowlers (357±22 BW·s^{-1}). Lower loading rate could be a factor that explains why the semi-open action is a relatively safe action-type (Portus, et al., 2004), since high loading rates in models of the vertebral spine increase the incidence of fractures, cause instability, and localise stresses on the vertebral structures (El-Rich, et al., 2009; Neumann, et al., 1996; Wagnac, et al., 2012). No data was available for collection during the back-foot contact phase for this current study and while GRFs have been reported during back-foot contact in adult bowlers (Hurrion, Dyson, & Hale, 2000; Portus, et al., 2004), no research has elaborated on lumbar loading during the back-foot contact phase in junior and adult bowlers. As has been highlighted in the current study, the major differences in trunk motion occurring during the back-foot contact phase, including shoulder counter-rotation, shoulder-pelvis separation at BIC, trunk rotation and T12-L1 ROM justify the exploration of lumbar loading during the back-foot contact phase.

This current study analysed kinetic variables for most body segments from the ankle to the T12-L1 section. Despite the differences in vertical GRF loading rate, no between-group differences were seen for any joint moments or lumbar joint forces. This may suggest once bowlers begin the front-foot contact phase, load is transferred along the kinetic chain at different rates in all three action-types.

There were a number of limitations identified by the authors in this study. Although every attempt was made to recreate match-like conditions, the unfamiliar laboratory environment may have affected participants' bowling performance. Wicket surface differed between cohorts/laboratories with a 20 mm athletic track for (Season 1 *n*=37) and a concrete surface (Season 2 *n*=23) participants. With only enough force platforms available to measure GRF during the front-foot contact phase, we were unable to provide kinetic analysis during back-foot contact phase. The cohort of this study included a wide age-range for inclusion (12-18 years), normalising all kinetic variables relative to body weight or body weight times height to account for age differences. Although the sample size of this cohort was relatively large, the small size of the side-on action group ($n = 2$) led to this group being excluded from analysis. Two-dimensional alignment angles in fast bowling are subject to out of plane projection errors (Smith, et al., 2016), so we also calculated the trunk and pelvis angles about three-dimensional joint coordinate systems.

CONCLUSION

This study has provided an in-depth exploratory comparison of the fast bowling actions in junior cricketers. Kinematic differences included increased trunk and lumbar motion for the mixed bowling action during the back-foot contact phase and a trunk more rotated away from the bowling-arm at BIC for semi-open bowlers. During the front-foot contact phase, front-on bowlers displayed greater trunk rotation towards the bowling-arm, owing to the front-on action being more rotated towards the bowling-arm from BIC. Kinetic analysis during the front-foot contact phase observed a decreased vertical GRF loading rate in the semi-open action, although no significant differences in joint loading were observed. The kinematic differences seen in this study during the back-foot contact phase suggest that junior fast bowlers utilise different movement strategies during the back-foot contact phase of the fast bowling action to achieve similar outcomes during the front-foot contact phase. Furthermore, analysis of lumbar kinetics during the back-foot contact phase is warranted to establish whether differences in lumbar kinematics corresponds to changes in lumbar loading during this phase. Due to the exclusion of the side-on action owing to low sample size, further research is required to determine if this action significantly differs from the other fast bowling actions.

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ADDITIONAL MATERIALS

1. RJSP-2018-1275R1-Table 1-General Bowling Results
2. RJSP-2018-1275R1-Table 2-Kinematic ANOVA
3. RJSP-2018-1275R1-Table 3-Significant Kinematics
4. RJSP-2018-1275R1-Table 4-Kinetic ANOVA

5. RJSP-2018-1275R1-Appendicies V4

Table 1 Results of the mean (±SE) of the general bowling characteristics between action types, distribution and classification of fast bowling action types based on Ferdinands et al. (2014a).

Action type	Shoulder Alignment at BIC	Shoulder Counter-rotation	N	Age (yr)	Height (cm)	Body Mass (kg)	Ball Speed (km/h)	Approach Speed ($m \cdot s^{-1}$)
Side-on	<25°	<40°	2	-	-	-	-	-
Front-on	≥50°	<40°	14	15.2±0.4	179.3±2.6	67.7±3.1	87.6±2.2	5.4±0.04
Semi-open	25°≤ and <50°	<40°	18	14.5±0.3	176.8±2.3	66±2.7	86.0±1.9	5±0.05
Mixed	N/A	>40°	26	14.3±0.3	175.9±1.9	64.3±2.3	86.5±1.6	5.4±0.04

Table 2 Mean (±SE) of all back-foot lower limb and front-foot lower limb joint angles in degrees (°) across action types.

Angle	Stage	Front-on	Semi-open	Mixed	Front-on	Semi-open	Mixed	Front-on	Semi-open	Mixed
Back-foot Lower Limb Angles										
		Dorsiflexion(+)/Plantarflexion(-)			*Inversion(+)/Eversion(-)*			*Forefoot Adduction(+)/Abduction(-)*		
Ankle	BIC	-22.2 ± 1.9	-20.9 ± 1.7	-18.8 ± 1.4	11 ± 1.6	12.8 ± 1.4	11 ± 1.2	4.6 ± 2.1	2.7 ± 1.9	8.2 ± 1.6
	FIC	-11.1 ± 4.7	-8.7 ± 4.1	-13.6 ± 3.5	16.1 ± 2.3	14.1 ± 2.1	15 ± 1.7	1.2 ± 3.9	-9.8 ± 3.4	4.7 ± 2.9
		Flexion(+)/Extension(-)			*Adduction(+)/Abduction(-)*			*Internal(+)/External(-) Rotation*		
Knee	BIC	27.6 ± 1.9	29.6 ± 1.7	31.8 ± 1.4	-1.1 ± 1.3	-1.5 ± 1.2	0.1 ± 1	-0.9 ± 2.3	-0.6 ± 2	-0.2 ± 1.7
	FIC	54.8 ± 2.5	50.4 ± 2.2	54.5 ± 1.9	-10.2 ± 1.5	-12.1 ± 1.3	-10.3 ± 1.1	0.2 ± 1.9	-0.3 ± 1.7	1.2 ± 1.4
Hip		*Flexion(+)/Extension(-)*			*Adduction(+)/Abduction(-)*			*Internal(+)/External(-) Rotation*		
	BIC	31.7 ± 2.7	27.4 ± 2.4	32.2 ± 2	-1.2 ± 1.8	-1.6 ± 1.6	-7.5 ± 1.3	-6.9 ± 2.9	-9.1 ± 2.6	-11.9 ± 2.2
	FIC	2.3 ± 2.5	1.1 ± 2.2	1.2 ± 1.8	-3.8 ± 2.3	-10 ± 2.1	-5.2 ± 1.7	-3.1 ± 2.7	-6.1 ± 2.4	-3.5 ± 2
Front-foot Lower Limb Angles										
		Dorsiflexion(+)/Plantarflexion(-)			*Inversion(+)/Eversion(-)*			*Forefoot Adduction(+)/Abduction(-)*		
	FIC	3.1 ± 3.9	6.6 ± 3.4	-1 ± 2.9	7.4 ± 1.8	4.0 ± 1.6	5.4 ± 1.3	-8.6 ± 2.8	-11.2 ± 0.5	-8.3 ± 2.1
	FV	-20.5 ± 2.5	-17.0 ± 2.2	-18.2 ± 1.9	-1.7 ± 2.9	-0.2 ± 2.5	-2.6 ± 2.2	-6.4 ± 2.8	-8.2 ± 2.4	-3.9 ± 2.1
Ankle	AH	-17.6 ± 2.3	-15.1 ± 2	-17.5 ± 1.7	-0.2 ± 3	0 ± 2.6	-2.4 ± 2.2	-9.2 ± 2.5	-10.7 ± 2.2	-5.3 ± 1.9
	BR	-3.9 ± 3.1	-3.7 ± 2.7	-9 ± 2.3	-0.6 ± 2.3	0 ± 2	-1.7 ± 1.7	-7.1 ± 2.8	-8.2 ± 2.5	-4.2 ± 2.1
	AV	-8.8 ± 2.7	-9 ± 2.3	-13 ± 2	5.8 ± 1.8	4.4 ± 1.6	3.3 ± 1.3	-6.8 ± 2.9	-4.2 ± 2.6	-1.6 ± 2.2
		Flexion(+)/Extension(-)			*Adduction(+)/Abduction(-)*			*Internal(+)/External(-) Rotation*		
	FIC	13.1 ± 2	19.4 ± 1.8	19.3 ± 1.5	0.3 ± 1.1	0.6 ± 1	-0.2 ± 0.8	-15.7 ± 2.7	-17.1 ± 2.4	-16.3 ± 2.1
	FV	16.5 ± 2	23.6 ± 1.7	19.2 ± 1.5	-0.9 ± 1.5	-0.8 ± 1.3	-0.4 ± 1.1	-11.3 ± 2.3	-9.1 ± 2.1	-11.7 ± 1.7
Knee	AH	25.4 ± 3.1	31.8 ± 2.7	26.5 ± 2.3	-1.3 ± 1.5	-0.2 ± 1.3	-0.4 ± 1.1	-8.4 ± 2.1	-6.5 ± 1.9	-8.7 ± 1.6
	BR	44.1 ± 5.4	45.4 ± 4.8	38.3 ± 4.1	-3.8 ± 1.7	-3.4 ± 1.5	-1.7 ± 1.7	1.5 ± 1.9	-0.6 ± 1.7	-4.2 ± 2.1
	AV	32.3 ± 6.1	30.6 ± 5.4	23.3 ± 4.6	-5 ± 1.5	-3.6 ± 1.3	-2.7 ± 1.1	-1.5 ± 2.1	-2.3 ± 1.8	-5.1 ± 1.6
		Flexion(+)/Extension(-)			*Adduction(+)/Abduction(-)*			*Internal(+)/External(-) Rotation*		
	FIC	44.0 ± 2.9	43.4 ± 2.5	40.5 ± 2.1	-31.3 ± 1.6	-32.3 ± 1.4	-34.1 ± 1.2	-21.4 ± 3.5	-16 ± 3.1	-16.8 ± 2.6
	FV	52.2 ± 2.6	53.9 ± 2.3	49 ± 2	-23.4 ± 1.8	-26 ± 1.6	-28.1 ± 1.3	-9.5 ± 3.4	-8.4 ± 3	-10.5 ± 2.6
Hip	AH	59.5 ± 2.9	61.2 ± 2.5	57.5 ± 2.1	-14.7 ± 2.3	-19 ± 2	-20.9 ± 1.7	-1.3 ± 4	0.1 ± 3.5	-2.7 ± 3
	BR	64.4 ± 2.9	64.1 ± 2.5	63.5 ± 2.1	3.3 ± 2	-2.7 ± 1.8	-3.7 ± 1.5	10.5 ± 3.3	10.6 ± 2.9	9.8 ± 2.5
	AV	50.6 ± 3.5	49.7 ± 3.1	53.1 ± 2.6	-4.4 ± 1.9	-8.7 ± 1.7	-7.1 ± 1.4	6.3 ± 3.1	4.2 ± 2.7	4.4 ± 2.3

Table 2 Results of the mixed-design factorial ANOVA of the main effect and interactions for all kinematic variables including joint angles, alignment angles, alignment angles and lumbothoracic intersegmental angle ROM.

Joint Angles						
	Actions			Stages*Angles*Actions		
	$F_{2,54}$	P	η_p^2	F	P	η_p^2
Back-foot lower limb	2.9	0.06	0.0981	$_{16,432}$=1.85	0.02	0.0642
Front-foot lower limb	1.12	0.33	0.0397	$_{64,1728}$=1.13	0.23	0.0400
Lumbothoracic	1.01	0.37	0.0362	$_{50,1350}$=1.4	0.03	0.0495
Bowling upper-arm	1.6	0.21	0.0555	$_{30,60}$=1.8	< 0.001	0.0624
Trunk-pelvis	3.87	0.03	0.1252	$_{80,2160}$=2.09	< 0.001	0.0718
Alignment Angles						
	Actions			Align*Actions		
	$F_{2,54}$	P	η_p^2	$F_{20,540}$	P	η_p^2
Alignment angles	33.15	< 0.001	0.5511	7.52	< 0.001	0.2179
Lumbothoracic intersegmental angle ROM						
	Actions			ROM*Actions		
Phase	$F_{2,54}$	P	η_p^2	$F_{10,270}$	P	η_p^2
Back-foot contact	3.13	0.052	0.1039	3.48	< 0.001	0.1141
Front-foot contact	0.69	0.51	0.0247	1.47	0.15	0.0517

Table 3 Outcomes of *post-hoc* analysis for all statistically significant ANOVA results for the mean (±SE) of the kinematic data. Units for all variables are reported in degrees (°). N.B. Each action type is assigned a numerical value to distinguish between multiple significant differences within each variable.

Angle	Stage	Front-on[1]	Semi-open[2]	Mixed[3]	*P*	*d*
Back-foot ankle inversion	FIC	4.6 ± 2.1	-9.8 ± 3.5	4.7 ± 2.9	< 0.001[2,3]	1.76[2,3]
T12-L1 left-rotation	BIC	-12.1 ± 2.5	-6.6 ± 2.2	-15.7 ± 1.9	0.01[2,3]	0.54[2,3]
Elbow pronation	BIC	79.1 ± 12.2	111.1 ± 10.7	115.3 ± 9.1	0.001[1,2], < 0.001[2,3]	0.24[1,2], 0.35[2,3]
	FIC	72.8 ± 9.3	49.5 ± 8.2	85.2 ± 6.9	< 0.001[2,3]	1.56[2,3]
	FV	64.6 ± 8.8	43.9 ± 7.8	75.4 ± 6.6	< 0.001[2,3]	1.62[2,3]
Trunk-pelvis right-rotation	BIC	13.4 ± 2.6	6.2 ± 2.3	18.6 ± 1.9	0.01[2,3]	0.63[2,3]
Trunk left-rotation	BIC	-30.8 ± 2.7	-50.6 ± 2.4	-27.4 ± 2	< 0.001[1,2] < 0.001[2,3]	1.97[1,2], 1.7[2,3]
	BR	-12.2 ± 4.3	-25.9 ± 3.8	-30.5 ± 3.2	0.03[1,2], < 0.001[1,3]	0.13[1,2], 0.86[1,3]
Trunk right-rotation	AV	25.9 ± 4.2	12.8 ± 3.2	10.9 ± 3.8	0.003[1,2], 0.02[1,3]	0.39[1,2], 1.12[1,3]
Shoulder alignment	BIC	61.5 ± 2.2	40.3 ± 1.9	67.3 ± 1.6	< 0.001[1,2], < 0.001 [2,3]	4.32[1,2], 5.07[2,3]
Peak shoulder alignment		26.6 ± 2.2	12.2 ± 1.9	18.2 ± 1.6	0.02	2.06
Shoulder counter-rotation		35 ± 1.8	28.1 ± 1.6	49.1 ± 1.3	0.008[1,3], < 0.001[2,3]	1.57[1,3], 2.19[2,3]
Shoulder-pelvis separation angle	BIC	20.4 ± 2.8	10 ± 2.5	27 ± 2.1	< 0.001	1.2
T12-L1 rotation ROM	BIC-FIC	27.8 ± 3.6	25 ± 3.2	36.4 ± 2.7	0.007[1,3], < 0.001[2,3]	0.08[1,3], 0.57[2,3]

Table 3 Mean (±SE) for all lumbothoracic joint angles and range of motion in degrees (°) across action types.

Angle	Stage	Front-on	Semi-open	Mixed	Front-on	Semi-open	Mixed	Front-on	Semi-open	Mixed
Lumbothoracic Angles										
		Flexion(+)/Extension(-)			*Left (+)/Right (-) Lateral Flexion*			*Left (+)/Right (-) Rotation*		
L5-S1	BIC	0.7 ± 2.6	1.0 ± 2.3	1.2 ± 2.0	1.5 ± 1.0	1.6 ± 0.9	2.3 ± 0.8	-1.3 ± 0.7	0.0 ± 0.6	-1.2 ± 0.5
	FIC	-4.9 ± 2.3	-5.2 ± 2.1	-4.4 ± 1.7	2.8 ± 1.0	2.5 ± 0.9	4.2 ± 0.8	0.8 ± 0.7	1.5 ± 0.6	1.3 ± 0.5
	FV	-6.0 ± 2.2	-6.8 ± 2.0	-5.8 ± 1.7	3.3 ± 1.1	2.5 ± 1.0	4.5 ± 0.8	0.8 ± 0.7	1.6 ± 0.6	1.4 ± 0.5
	AH	-4.1 ± 2.5	-5.2 ± 2.2	-3.9 ± 1.9	3.4 ± 1.2	2.5 ± 1.0	4.7 ± 0.9	0.7 ± 0.8	1.6 ± 0.7	1.1 ± 0.6
	BR	7.9 ± 2.8	6.7 ± 2.4	7.4 ± 2.1	2.8 ± 1.2	2.0 ± 1.1	3.9 ± 0.9	-0.5 ± 0.8	0.0 ± 0.7	-0.4 ± 0.6
	AV	11.7 ± 2.9	11.8 ± 2.6	11.0 ± 2.2	0.0 ± 1.0	0.1 ± 0.9	1.5 ± 0.8	-1.7 ± 0.6	-1.4 ± 0.5	-1.4 ± 0.5
		Flexion(+)/Extension(-)			*Left (+)/Right (-) Lateral Flexion*			*Left (+)/Right (-) Rotation*		
T12-L1	BIC	4.4 ± 2.4	1.5 ± 2.1	3.9 ± 1.8	-2.9 ± 1.8	-1.8 ± 1.6	-5.3 ± 1.3	-12.1 ± 2.5	-6.6 ± 2.2	-15.7 ± 1.9
	FIC	0.4 ± 2.3	-2.3 ± 2.0	2.7 ± 1.7	4.0 ± 2.3	-0.6 ± 2.0	1.4 ± 1.7	11.7 ± 2.3	14.0 ± 2.0	16.7 ± 1.7
	FV	-5.0 ± 2.2	-7.0 ± 1.9	-3.0 ± 1.6	7.8 ± 2.1	6.1 ± 1.9	7.3 ± 1.6	19.4 ± 2.6	19.1 ± 2.3	23.5 ± 1.9
	AH	-6.6 ± 2.2	-10.2 ± 1.9	-6.2 ± 1.6	14.9 ± 2.1	11.6 ± 1.9	13.5 ± 1.6	20.1 ± 3.1	22.8 ± 2.7	26.6 ± 2.3
	BR	13.1 ± 2.6	11.5 ± 2.3	12.3 ± 1.9	25.6 ± 2.1	26.4 ± 1.9	27.3 ± 1.6	10.2 ± 2.8	12.2 ± 2.5	17.9 ± 2.1
	AV	22.2 ± 2.4	23.3 ± 2.2	26.4 ± 1.8	-2.8 ± 2.6	3.1 ± 2.3	-0.4 ± 2.0	-13.0 ± 2.5	-10.9 ± 2.2	-14.8 ± 1.9
Lumbothoracic Range of Motion										
		Flexion(+)/Extension(-)			*Left (+)/Right (-) Lateral Flexion*			*Left (+)/Right (-) Rotation*		
L5-S1	BIC-FIC	10.6 ± 1.2	11.8 ± 1.1	10.3 ± 0.9	2 ± 0.3	2.1 ± 0.2	2.1 ± 0.2	2.4 ± 0.4	2.6 ± 0.4	3 ± 0.3
	FIC-BR	15.2 ± 1.5	15.6 ± 1.3	14.4 ± 1.1	2 ± 0.4	2.4 ± 0.3	1.7 ± 0.3	2.4 ± 0.4	3.1 ± 0.4	2.7 ± 0.3
		Flexion(+)/Extension(-)			*Left (+)/Right (-) Lateral Flexion*			*Left (+)/Right (-) Rotation*		
T12-L1	BIC-FIC	7.8 ± 1	8.7 ± 0.9	10.6 ± 0.8	8.8 ± 1.3	9.4 ± 1.2	10.3 ± 1	27.8 ± 3.6	25 ± 3.2	36.4 ± 2.7
	FIC-BR	22.1 ± 1.6	23.7 ± 1.4	22.4 ± 1.2	26.2 ± 1.7	30.4 ± 1.5	29.1 ± 1.3	15.5 ± 1.8	15.2 ± 1.6	19 ± 1.3

Table Mean (±SE) for all bowling arm joint angles in degrees (°) across action types.

Angle	Stage	Front-on	Semi-open	Mixed	Front-on	Semi-open	Mixed	Front-on	Semi-open	Mixed
		Forward Flexion(+)/Extension(-)			*Adduction(+)/Abduction(-)*			*Internal(+)/External(-) Rotation*		
Shoulder	BIC	44.6 ± 4.2	40.2 ± 3.7	52.2 ± 3.1	10.1 ± 3	9.3 ± 2.6	11.6 ± 2.2	12.1 ± 8.9	29.1 ± 7.9	31.9 ± 6.7
	FIC	-14.1 ± 4.5	-14.4 ± 4	-9.9 ± 3.4	-38.6 ± 2.9	-41.1 ± 2.6	-36.2 ± 2.2	-62.1 ± 7.2	-59.2 ± 6.4	-63.9 ± 5.4
	FV	-39.6 ± 6.7	-45.2 ± 5.9	-35.8 ± 5	-46.1 ± 2.7	-47.9 ± 2.4	-45.1 ± 2	-103.4 ± 6.5	-101.4 ± 5.8	-105.4 ± 4.9
	AH	-49.3 ± 6.4	-52.7 ± 5.6	-47.4 ± 4.8	-43.8 ± 3.2	-49.5 ± 2.8	-44.3 ± 2.4	-120.3 ± 7	-115 ± 6.1	-125.2 ± 5.2
	BR	-122.5 ± 7.3	-123.2 ± 6.4	-117.6 ± 5.5	-56.9 ± 3.2	-63.4 ± 2.8	-61.2 ± 2.4	-196.2 ± 10.8	-179.4 ± 9.5	-200.7 ± 8.1
	AV	-295.8 ± 3.6	-291 ± 3.2	-291.2 ± 2.7	-18 ± 3	-9.1 ± 2.6	-15.1 ± 2.2	-320.2 ± 7.9	-300.5 ± 7	-321.4 ± 5.9
		Flexion(+)/Extension(-)			*Cross-talk Not Reported*			*Pronation(+)/Supination(-)*		
Elbow	BIC	28.7 ± 6.2	41.7 ± 5.5	31.4 ± 4.7				79.1 ± 12.2	111.1 ± 10.7	115.3 ± 9.1
	FIC	15.1 ± 2.8	11.8 ± 2.4	17.6 ± 2.1				72.8 ± 9.3	49.5 ± 8.2	85.2 ± 6.9
	FV	17 ± 3.2	12.3 ± 2.8	18.3 ± 2.4				64.6 ± 8.8	43.9 ± 7.8	75.4 ± 6.6
	AH	17.3 ± 3.5	12.1 ± 3	18.7 ± 2.6				60.8 ± 9	43.9 ± 7.9	74.5 ± 6.7
	BR	18 ± 3	14 ± 2.6	18.3 ± 2.2				70.5 ± 8.7	57 ± 7.7	78.7 ± 6.5
	AV	27.5 ± 1.7	26.6 ± 1.5	27.4 ± 1.3				112.5 ± 5.4	109.6 ± 4.7	112.8 ± 4

Table A6 Mean (±SE) for all trunk-pelvis, trunk and pelvis angles in degrees (°) across action types.

Angle	Stage	Front-on	Semi-open	Mixed	Front-on	Semi-open	Mixed	Front-on	Semi-open	Mixed
		Extension(+)/Flexion(-)			*Right (+)Left (-) Lateral Flexion*			*Right (+)/Left (-) Rotation*		
Trunk-Pelvis	BIC	-5.6 ± 3.4	-3.6 ± 3	-6.4 ± 2.5	0 ± 1.5	0.4 ± 1.4	-0.7 ± 1.2	13.4 ± 2.6	6.2 ± 2.3	18.6 ± 1.9
	FIC	3.6 ± 2.9	8.1 ± 2.6	1.5 ± 2.2	-2.7 ± 1.2	-0.7 ± 1.1	-4 ± 0.9	-15.7 ± 2	-16.9 ± 1.8	-19 ± 1.5
	FV	7.5 ± 3	11.9 ± 2.7	5.5 ± 2.3	-11 ± 1.4	-9.5 ± 1.3	-12.2 ± 1.1	-20.4 ± 2.5	-20.6 ± 2.2	-25 ± 1.9
	AH	4.9 ± 3.2	9.1 ± 2.8	3.2 ± 2.4	-17.1 ± 1.7	-16.3 ± 1.5	-18.9 ± 1.3	-21.9 ± 3	-22.9 ± 2.6	-28.2 ± 2.2
	BR	-27.5 ± 3.6	-26.8 ± 3.2	-30.2 ± 2.7	-23.2 ± 1.7	-25.1 ± 1.5	-26.9 ± 1.3	-18.3 ± 3.2	-19.2 ± 2.8	-26.5 ± 2.4
	AV	-33.1 ± 3.3	-31.7 ± 2.9	-36.1 ± 2.5	-6.4 ± 1.7	-12.1 ± 1.5	-12 ± 1.3	16.5 ± 2.8	7.9 ± 2.5	15 ± 2.1
		Extension(+)/Flexion(-)			*Right (+)Left (-) Lateral Flexion*			*Right (+)/Left (-) Rotation*		
Pelvis	BIC	4.4 ± 2	10.6 ± 1.7	8.4 ± 1.5	9.6 ± 1.9	8.1 ± 1.7	10.8 ± 1.4	-45.4 ± 3.1	-57.4 ± 2.7	-47.4 ± 2.3
	FIC	-8.9 ± 1.6	-7.7 ± 1.4	-6.5 ± 1.2	-6.6 ± 1.8	-2 ± 1.6	-9.6 ± 1.4	-40.3 ± 2.7	-50.5 ± 2.4	-46.5 ± 2
	FV	-14.6 ± 1.6	-15.7 ± 1.4	-14.1 ± 1.2	-8.4 ± 1.6	-5.3 ± 1.5	-11.9 ± 1.2	-25.8 ± 2.4	-33.4 ± 2.1	-30.7 ± 1.8
	AH	-16.6 ± 1.8	-17.1 ± 1.6	-16.4 ± 1.3	-8.9 ± 1.6	-6 ± 1.4	-12.3 ± 1.2	-16.9 ± 2.9	-25.2 ± 2.6	-20.8 ± 2.2
	BR	-19.5 ± 2.1	-19.2 ± 1.9	-19.4 ± 1.6	-16.1 ± 1.9	-13.7 ± 1.7	-19.8 ± 1.4	13.7 ± 3.2	3.3 ± 2.8	8.2 ± 2.4
	AV	-33.1 ± 2.6	-33.5 ± 2.3	-37 ± 2	-24.8 ± 2.1	-22.1 ± 1.9	-27.1 ± 1.6	28.6 ± 3.6	18.8 ± 3.2	20.7 ± 2.7
		Extension(+)/Flexion(-)			*Right (+)Left (-) Lateral Flexion*			*Right (+)/Left (-) Rotation*		
Trunk	BIC	0 ± 2.8	8.5 ± 2.5	3.5 ± 2.1	13.6 ± 2.1	11.3 ± 1.9	14.7 ± 1.6	-30.8 ± 2.7	-50.6 ± 2.4	-27.4 ± 2
	FIC	-7.9 ± 2.1	-2.9 ± 1.8	-8 ± 1.5	-11.4 ± 1.9	-8.6 ± 1.6	-13.5 ± 1.4	-56 ± 2.3	-67.3 ± 2	-65.9 ± 1.7
	FV	-12.7 ± 2.3	-11.6 ± 2	-15.3 ± 1.7	-23.1 ± 1.8	-20.2 ± 1.6	-26 ± 1.4	-47.1 ± 4.9	-54.6 ± 4.3	-53.4 ± 3.6
	AH	-16.2 ± 2.7	-16.3 ± 2.4	-20.3 ± 2	-27.4 ± 1.8	-25.3 ± 1.6	-31.3 ± 1.3	-39.2 ± 4.1	-49.6 ± 3.7	-50.8 ± 3.1
	BR	-44.9 ± 3.9	-50.6 ± 3.5	-54 ± 2.9	-44.4 ± 2.4	-39 ± 2.2	-48.2 ± 1.8	-12.2 ± 4.3	-25.9 ± 3.8	-30.5 ± 3.2
	AV	-68.3 ± 4.2	-72.7 ± 3.7	-80 ± 3.1	-43 ± 2.5	-39.8 ± 2.2	-45.7 ± 1.9	25.9 ± 4.2	12.8 ± 3.2	10.9 ± 3.8

Table A8 Mean (±SE) for all alignment angles in degrees (°) across action types.

Angle	Front-on	Semi-open	Mixed
Back-foot Angle	29.9 ± 2.3	32.9 ± 2	29 ± 1.7
Front-foot Angle	7.6 ± 2.9	2.3 ± 2.6	2.4 ± 2.2
Pelvis Alignment BIC	41.2 ± 3.6	30.6 ± 3.2	41.3 ± 2.7
Pelvis Alignment Peak	32.4 ± 3.5	19.1 ± 3	23.3 ± 2.6
Pelvis Counter-rotation	8.9 ± 2.1	11.5 ± 1.9	16.9 ± 1.6
Shoulder Alignment BIC	61.5 ± 2.2	40.3 ± 1.9	67.3 ± 1.6
Shoulder Alignment Peak	26.6 ± 2.2	12.2 ± 1.9	18.2 ± 1.6
Shoulder Counter-rotation	35 ± 1.8	28.1 ± 1.6	49.1 ± 1.3
Shoulder-pelvis Separation BIC	20.4 ± 2.8	10 ± 2.5	27 ± 2.1
Shoulder-pelvis Separation FIC	-23.3 ± 2.2	-25.1 ± 2	-25.5 ± 1.7
Shoulder-pelvis Separation Peak	31.1 ± 2.8	37.8 ± 2.5	38 ± 2.1

Table 4 Results of the mixed-design factorial ANOVA of the main effect and interactions for all kinetic variables including ground reaction force data, joint moments and joint forces.

Ground Reaction Forces						
	Actions			Force*Actions		
	$F_{2,53}$	P	η_p^2	$F_{14,371}$	P	η_p^2
Forces	4.21	0.02	0.1372	4.22	< 0.001	0.1373
	Actions			Impulse*Actions		
	$F_{2,53}$	P	η_p^2	$F_{8,212}$	P	η_p^2
Impulses	0.74	0.48	0.0272	0.84	0.57	0.0308
	Actions			Timing*Actions		
	$F_{2,53}$	P	η_p^2	$F_{14,371}$	P	η_p^2
Time to peak GRF	2.05	0.14	0.0717	0.89	0.57	0.0324
Joint Moments						
	Actions			Moment*Actions		
	$F_{2,50}$	P	η_p^2	F	P	η_p^2
Lower Limb	0.61	0.55	0.0237	$_{34,850}=0.81$	0.77	0.0316
Lumbothoracic	0.32	0.73	0.013	$_{22,539}=1.12$	0.32	0.0437
Joint Forces						
	Actions			Joint Force*Actions		
	$F_{2,53}$	P	η_p^2	$F_{12,318}$	P	η_p^2
Lumbothoracic	1.73	0.19	0.0612	1.4	0.16	0.0502

Table A11 Mean (±SE) for all peak joint forces (relative to BM) across action types.

Joint	Force	Front-on	Semi-open	Mixed
L5-S1	Lateral flexion	0.8 ± 0.09	0.92 ± 0.08	0.96 ± 0.07
	Anterior	1.79 ± 0.11	1.46 ± 0.1	1.66 ± 0.09
	Compressive	0.77 ± 0.07	0.7 ± 0.06	0.71 ± 0.05
T12-L1	Lateral flexion	1.29 ± 0.11	1.2 ± 0.1	1.33 ± 0.08
	Anterior	1.36 ± 0.09	1.06 ± 0.09	1.22 ± 0.07
	Posterior	0.6 ± 0.05	0.46 ± 0.05	0.49 ± 0.04
	Compressive	0.89 ± 0.07	0.8 ± 0.07	0.77 ± 0.06