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Manuscript Title: The role of the trunk control in athletic performance of a reactive change-of-direction task

Running Head: Performance during a reactive change-of-direction task

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ABSTRACT

Agility is vital to success in team sport competition with the trunk argued to play a key role in sport performance. This study explored the role of trunk control during a reactive change-of-direction task (R-COD) and field-based measures of athletic performance. Twenty male players completed field-based athletic performance assessments (modified Illinois agility test (mIAT), and three repetition maximum back squat (3RM)), and five countermovement jumps (CMJ) and R-CODs during which, three-dimensional ground reaction forces (GRF) and kinematics were recorded. Trunk control was assessed as the sum of the trunk relative to the pelvis range of motion in all three plane during the R-COD. Participants with the highest (HIGH; n = 7) and lowest (LOW; n = 7) trunk **range of motion** values were grouped. The HIGH group achieved significantly shorter mIAT time duration, higher CMJ height, and lower knee flexion angles, greater trunk lateral flexion and rotation relative to pelvis, and greater angular momentum during the R-COD compared with the LOW group. Superior athletic performance was associated with decreased trunk control **(high trunk range of motion)** during the R-COD. **Whilst this study** suggesting that trunk **control** is a vital component of performance, **it is unknown whether this trunk control is inherent or an effect of training history, nor** does not support current optimal athletic performance **recommendation of** decrease trunk motion during R-COD.

Key Words: sidestepping; biomechanics; performance; lumbopelvic

INTRODUCTION

A critical aspect of field and court sports performance is agility that requires athletes to decelerate, quickly re-orientate the body in a new direction and rapidly accelerate in response to game conditions as well as strategic and tactical demands (38). It is theorized that the core operates to form a link between the upper and lower limbs by controlling posture and force interplay across the musculoskeletal system (6). Previous research has poorly defined the "core" and described it using ambiguous terms dependent on the context of the research (14, 19, 44), such as trunk, core, lumbar region, low back, lumbo-pelvic region, and lumbo-pelvic hip complex. The lack of clear terminology and well defined concepts makes selection of valid assessment tools difficult, increasing the risk of methodological error and possibly contributing to the lack of a gold standard assessment tool being developed (14). Therefore, the term "trunk control" previously used to investigate trunk mechanics during a R-COD (18-20) will be used from here on. It is defined according to Zazulak, Cholewicki and Reeves (44) as "the capacity of the body to maintain or resume a relative position (static) or trajectory (dynamic) of the trunk following perturbation".

Bergmark (6) proposed that force is imparted via structures of the trunk that work together to control posture, maintain stability and distribute force across the system. Stability is maximized by the motor control system through the coordinated co-contraction of musculature that must preserve stability by maintaining a balanced tension acting on the system at a given moment in time (26, 28). Loss of tension within the trunk may cause the trunk to buckle, as such, synchronization of muscle activity across the system is vital to maintain stability (28, 29). A strategy adopted by the trunk during high loading is to increase stiffness of the spine through co-contraction of core musculature via minimizing excess motion during motions such as weight training, power lifting and strongman events (29) and agility tasks (35).

To optimize agility performance, it has been recommended that athletes need minimal pelvis tilt (25) and trunk flexion range of motion, to flex their trunk (35, 38), in order to re-orientate their trunk and pelvis towards the direction of travel (35). By adapting a trunk flexion posture, it is thought to optimize acceleration and deceleration characteristics (35, 38) and lower the athletes center of mass (39) to enable the athlete to apply more force in the intended direction of travel (42). Furthermore, faster agility performance has also been associated with greater thorax rotation towards direction of anticipated 75° cut (25).

Evidence on improving athletic performance from training studies support the suggestion that a strong and stable trunk is conflicting, with correlations between performance and core assessments only ranging from weak to moderate (19, 31, 40). Clinical assessments of the core have used endurance as a correlate of control due to the correlation of lower back pain with decreased endurance times and core musculature weakness for static postures (32), such as those used in the McGill protocol (27). While endurance is a critical aspect of performance in a number of sporting events, assessing the endurance of the trunk musculature is unlikely to give a clear indication of an athletes' ability to absorb, transfer, control and/or dissipate forces acting on or through the body during agility movements. Assessments of core power previously described in research (31, 40) using medicine ball throws from static and non-sport specific postures may be reliable, however, the validity of such tests to dynamic field and court sport environments, in which athletes are in motion, may be questionable.

The cut task, a frequently performance agility movement in sport, has high validity for team sports, and has previously been used to assess the influence of the absolute trunk segment relative to the global coordinate system motion on injury (11, 20, 30) and athletic performance (12, 25, 35). Nevertheless, this absolute trunk angle does not take into account the orientation of the pelvis nor whether the participant is running in a straight line, which both may affect the magnitude of the absolute trunk angle. Furthermore, field-based assessments of athletic performance have reported conflicting between-study differences between agility performance, and the back squat (21, 42), countermovement jump height (13, 36) and sprinting (36).

Therefore, the aim of this present study is to explore the role of trunk control during an R-COD with a defensive opponent with field-based measures of athletic performance. It is hypothesized that participants displaying higher trunk control **(low trunk range of motion)** during a R-COD with a defensive opponent will display superior performance in field-based measures of athletic performance compared to those participants displaying lower trunk control **(high trunk range of motion).**

MATERIAL AND METHODS

Participants

Twenty male team sport athletes **(age range 19 to 27 years)** with no history of previous traumatic lower limb injury requiring surgery were recruited **(mean age = 21.6 ± 2.1 years; height = 183.2 ± 5.9 cm; mass = 89.9 ± 13.7 kg)**. Participants' dominant lower limb was identified as the limb contacting a ball during kicking, as it was the preferred lower limb utilized to change of direction. Written informed consent was obtained from each participant prior to data collection and all methods were approved by the institutions' Human Research Ethics Committee.

Experimental Protocol

The experimental protocol involved three sessions, a familiarization session of the performance session, followed by, in any order, a performance session and a biomechanical session. The performance session included a mIAT, 3RM back squat, core endurance tests, static control tests, and the biomechanical session included a CMJ and R-COD with a defensive opponent. **Each participant performed the biomechanical and the performance session at the same time of the day but there were between-participant differences in the time of day they each performed their sessions.**

Performance Session

Participants performed three trials of a mIAT with 5 mins self-paced waking recovery between (fastest recorded), which required the participant to complete the Illinois agility test course (1) twice. For the 3RM back squat test, an Olympic barbell was loaded with 50% of the reported history 1RM squat load of the participant, rounded to the nearest 10 kg increment. With each successful 3RM trial, as defined according to Baechle, Earle, National and Conditioning (3), the load was increased between 5 to 20 kg based on observation of the participants' effort of the previous lift, until a successful maximum 3RM was reached by the participant.

As per the protocol developed by McGill et al (27), the core endurance tests involved the participant adopting one of four individual static postures once and to hold the static posture for as long as possible with 5 min rest between test. These postures in order included back extension, flexor endurance test, left side bridge and right side bridge (Figure 1). Each test was timed and terminated by the tester when the correct posture specific to each individual test could no longer be maintained by the participant.

Using a NeuroCom Balance (VSR SPORT, NeuroCom International, Clackamas, OR), each participants static control was assessed by performing a stability evaluation test and limits of stability test. Stability evaluation test was used to assess an individual's postural sway velocity during double, tandem and single limb stance position. Limits of stability assessed the ability of the participant to accurately and quickly voluntarily move their center of gravity location to eight pre-determined targets without losing balance (7).

<Insert Figure 1 about here>

Biomechanical Data Collection

Passive reflective markers were attached to each participant's skin on the torso, pelvis and lower limbs, and the shoe (23). To avoid passive marker concealment, participants wore minimal clothing and their own socks and athletic shoes during trials. Participants then completed 5 min of self-paced warm-up on a cycle ergometer at 1.5 kp (Monark Model 828E, Varburg, Sweden), five successful CMJ trials, followed by five successful trials of both a left and right unanticipated cut task with a defensive opponent. For both the CMJ and the R-COD, three-dimensional trunk and lower limb kinematics were captured (250 Hz) using an eight camera Oqus 300 motion system (Qualisys AB, Göteborg, Sweden), and the GRF data were recorded using two multi-channel force platforms with inbuilt charge amplifier (Type 9281CA and Type 9281EA, Kistler, Winterthur, Switzerland) embedded in the laboratory floor and fitted with an all-weather polyurethane running track material and connected to two control units (Type 5233A, Kistler, Winterthur, Switzerland).

Experimental Task

Participants were instructed to perform the CMJ by jumping vertically as high as possible, and were permitted one preparatory downward swinging motion of the arms and torso prior to launching vertically upwards with an upward swinging motion and arms extended overhead. A successful CMJ trial was defined as the participant launching and landing with each foot wholly contacting separate force platforms. CMJ height was calculated as the difference between the location of the center of mass when standing and the maximal height reached during the CMJ.

A R-COD (unanticipated cut task with a defensive opponent) involved participants starting from a line marked 7 m from the front edge of the force platform, running towards the dual force platforms with an approach speed of between 4.5 to 5.5 $m{\cdot}s^{-1}$ (Speed Light, Swift Sports Equipment, Lismore, Australia). On the participants approach to the force platforms, a signal was given manually by the author (AA) from either a red or green light directing the participant to either a left or right COD direction, in a randomized order. The participant reacted to the signal, performing a change of direction, stepping off the force platforms between lines marked on the floor at 30˚ and 60˚ from the axis of the running track, originating at the mid-point of the force platforms' medial borders. A plastic skeleton was situated 40 cm from the rear edge of the force platforms to mimic a defending player in a game environment. Completion of a successful R-COD trial required a participant to achieve the required approach speed, the foot of the support limb wholly contacting only on one or both force platforms, the contact limb being the opposite limb to the new direction of travel, and the cut in the direction of the corresponding light-emitting diode signal with the swing limb passing behind the support limb. To minimize the effects of fatigue, participants were given a 1 min rest between each trial, and a 5 min rest between each set of 20 trials (number of trials required to obtain successful trials: LOW 89 ± 30, range 41-143; HIGH 73 ± 28, range 31-100).

Data Reduction and Analysis

Using a customized LabView (2010, National Instruments, Austin, USA) software program, a fourth-order zero-phase-shift Butterworth digital low pass filter was used to filter raw GRF data (f_c = 50 Hz) before calculating the individual GRF variables. Analysis of the kinematic and joint kinetic data was performed using Visual 3D software (Version 4, C-Motion, Maryland, USA). The raw kinematic coordinates, GRFs, free moments and center of pressure data were filtered with a fourth-order zero-phase-shift Butterworth digital low pass filter (f_c = 18 Hz), before calculating individual joint kinematics and internal joint moments. Segmental mass and inertial properties definitions procedures are outlined in Mann, Edwards, Drinkwater and Bird (23).

All segments were defined as x-axis mediolateral, y-axis anterior-posterior and z-axis up-down direction to conserve Cartesian local coordinate system sign conventions. All intersegmental joint angles were expressed using a *xyz* Cardan sequence of rotation. The net internal joint moments were normalized in accordance with the participants' body mass to account for participants' variations. Calculated GRF impulse values were also normalized to participants' body weight. Using the 18 Hz filtered kinetic data, the weight acceptance (WA) phase was defined from initial contact (IC) when the vertical GRF exceeded 10 N to the first local minimum (F_{WA}) after the first peak vertical GRF (F_{V1}) (11). The propulsion phase (PP) was defined from F_{WA} to toe off (TO) during which the second peak vertical GRF (F_{V2}) occurred. The vertical GRF data were used to calculate temporal events (IC, and at the times of F_{V1}, F_{WA}, F_{V2}, and TO). Loading rate of F_{V1} (LR F_{V1}, bodyweight per second) was calculated by dividing F_{V1} by the time interval between IC and the time of F_{V1}. For each of the 5 successful cut trials for all the kinematic and kinetic variables. Kinematic variables included ankle, knee, hip, L5-S1, and T12-L1 joint kinematics at IC and at the times of F_{V1}, F_{WA}, F_{V2}, and TO, and location of the center of gravity relative to the foot were calculated. Kinetics variables included the peak net internal ankle, knee, hip, L5-S1, and T12-L1 joint moments that were identified between IC to TO, and the angular momentum of the model center of gravity at IC, TO, and the peak and change in angular momentum during the WA and PP phases. **Previous research during a change-of-direction task that these measure have displayed excellent reliability of the majority of the trunk and lower limb kinematics, and fair to good for most ground reaction forces, and knee and hip joint moments (25).** Although data for both lower limbs was recorded, only the data for the COD directions that utilized the dominant lower limb as the support limb was utilized for analysis purposes.

Statistical Analysis

Trunk control during the R-COD was assessed as the sum of the range of motion of the trunk relative to the pelvis from IC to TO in all three planes. The participants were ranked in order based on their trunk control and categorized into a higher range of motion (ROM) group (HIGH; n = 7) and a lower ROM group (LOW; n = 7; Figure 2). The middle ROM group (n = 6) was removed from analysis to ensure a significant between-group difference in total trunk relative to pelvis ROM during the R-COD.

<Insert Figure 2 about here>

Means and standard deviations were calculated for each outcome variable for participants in the HIGH and LOW groups for each kinetic and kinematic variable during the R-COD, peak CMJ height, mIAT, 3RM squat, and McGill protocol total and individual tests. After confirming normality with a Kolmogorov–Smirnov test with Lilliefors correction, the data were analyzed using a series of independent-samples *t*-tests ($P \leq 0.05$) to identify any significant between-group differences in the outcome variables. Granting there is an increase in likelihood of incurring an error due to multiple statistical comparisons being conducted, adjustment to the alpha level was deemed unnecessary due to the exploratory nature of the present study (34). Furthermore, the precision of estimation (95% confidence limit) and magnitude-based inferences (effect sizes, (8) were calculated to redress the deficiencies of Null Hypothesis significance testing based research (16). Effects were defined as unclear when confidence limits exceeded the change in mean, being the small effect size threshold, of the standard deviation on both sides of the null. Moderate or large effect sizes were defined as substantial (16). The precision of estimates is indicated by 95% confidence limits, which define the range representing the uncertainty in the true value of the sample mean. Approximately one third of the sample size on those based on hypothesis testing is required when utilizing an Bayesian approach (4) and therefore a minimum of seven participants per group were estimated based on our previous research. A customized Excel spread sheet was used for all statistical procedures (15).

RESULTS

Field-based performance variables

The HIGH group recorded significantly faster mIAT and higher CMJ height in comparison to the LOW group (Table 1). No significant differences in the control evaluation tests were observed during any stance position in either the firm or foam surface. The limits of stability test, the HIGH group displayed faster velocity during diagonal backward/dominant side direction but slower during the diagonal forward/non-dominant side direction.

<Insert Table 1 about here>

Kinematics

No significant differences were observed for any hip, L5-S1 joint, or T12-L1 joint angle variables nor location of the foot segment relative to the body center of mass (Table 2 and **Figure 3**). However, the HIGH group displayed significantly, smaller forefoot adduction angle at IC, and knee flexion angles at IC and TO when compared to the LOW group. The HIGH group utilized a significantly greater total (HIGH = 68.3 ± 8.0º, LOW = 44.1 ± 5.4º; P <0.001, d = 1.71, 95% confidence interval (CI) 8), flexion-extension (HIGH = 17.6 ± 4.5º, LOW = 12.4 ± 2.8º; P <0.02, d = 1.15, 95% CI 4.4) and rotation (HIGH = 33.1 ± 5.1º, LOW = 18.8 ± 3.9º; P <0.001, d = 1.66, 95% CI 5.3) trunk relative to pelvis range of motion during the R-COD compared to the LOW group (lateral flexion: HIGH = 17.7 ± 4.2º, LOW = 12.8 ± 5.4º; P = 0.08, d = 0.93, 95% CI 5.6). Trunk relative to pelvis joint angles were significantly larger for the HIGH group for right trunk rotation at time of IC, at the time of F_{V1} and at TO, and trunk lateral flexion to the right at times of F_{WA} and F_{V2} compared to the LOW group.

<Insert Table 2 and **Figure 3** about here>

Kinetics

No significant differences were observed in any of the GRF (**Table 3 and Figure 4**) nor peak joint moment variables between the HIGH and LOW groups throughout the R-COD (Table 5). During the WA phase, the HIGH group displayed significantly greater peak anterior and change in anteroposterior change angular momentum compared to the LOW group. Whereas for the mediolateral angular momentum, the HIGH group displayed a more neutral value at IC and greater peak angular momentum away from the direction of travel during the WA phase, and less away from the direction of travel at TO.

<Insert **Table 3 and Figure 4** about here>

DISCUSSION

Previous literature suggests that the trunk plays an integral part in athletic performance by forming a critical link between the upper and lower limbs, enabling optimal dissipation of force between body segments as a result of increase trunk control (6). This current study hypothesis was not supported as participants who utilized a **higher trunk control, LOW group (low trunk range of motion),** during a R-COD displayed poorer performance during field-based athletic performance tests. The LOW group (stable trunk) demonstrated this by significantly slower mIAT time and lower CMJ height when compared with the HIGH group (unstable trunk). No between-group differences were observed the in 20 m sprint time nor absolute or relative 3RM squat, which highlights the ambiguity of the between-studies difference in the relationship of these field-based assessments with agility (9, 21, 42). **The lower absolute and relative 3RM squat values in this current study compared to higher skilled team sport athletes at a professional (9) or semi-professional level (41), may have confounded the relationship between 3RM and athletic performance. Nevertheless, it is recommended to improve athletic performance, ground-based lifts (squats, dead lift and Olympic lifts) should be employed to train the core to improve athletic performance (5) due to the higher core muscular activation than core stability ball exercises (33). Nevertheless, the weak relationship 3RM squat between-groups suggests that performance of the squat, a ground-based lift, did not affect athletic performance in this current study. While the 'core' is recommended to be trained for athletic conditioning via performing these 'big 3' exercises (cleans, deadlifts and squats), it is possible that the transfer-of-training effect may be insufficient to elicit the use of the core to control the trunk in R-COD.**

Despite significant between-group differences in the field-based assessments of performance, there were no significant between-group differences observed for the hip, L5-S1, or T12-L1 joint angles, GRF variables, or any peak net internal ankle, knee, hip, L5-S1 or T12-L1 joints moments throughout the R-COD. It is acknowledged that this lack of statistically significant between-group differences in the plant-and-cut maneuver may be due to the limited sample sizes utilized within this present study. Nevertheless, despite the lack of statistically significant data, the magnitude of effect sizes indicates the strength of the relationship between-groups (4) and avoid the shortcomings of research based in null-hypothesis significance testing (16). Consequently, moderate and/or large effect sizes during a R-COD may assist in explaining why the HIGH group displayed superior performance in comparison with the LOW group in field-based performance measures. Therefore, due to the exploratory nature of this current study, moderate and/or large effect sizes will also be discussed to explore and assist explaining the significant between group differences between trunk control and performance during a R-COD.

The HIGH group displayed significant greater flexion-extension and rotation range of motion compared with the LOW group throughout the R-COD. Players with lower trunk control achieved this **higher trunk range of motion** by positioning their trunk more upright and rotated away from the direction of travel at IC, then they continued to laterally flex their trunk away from the direction of travel more as their flexed their trunk, and then rotated their trunk more towards the direction of travel as they became more upright and decreased their lateral flexion compared to the LOW group. This may enable these HIGH participants better athletic performance in the field-based test of performance by creating greater peak anterior, change in anteroposterior angular momentum during the WA phase and a neutral mediolateral angular momentum at IC, may have enabled the HIGH participant to effect a change of direction more rapidly towards the direction of travel.

A critical component of agility and team sport performance is the ability to develop higher acceleration and achieve maximal speed more quickly (24). This can be achieved during straight-line sprinting by athletes who are able to position the center of mass more anteriorly relative to the ground contact point to create a higher ratio of horizontal to vertical GRF (17). In this current study, the players with lower trunk control **(high trunk range of motion)** and superior agility performance displayed a moderately greater anterior position of the foot relative to the body center of mass at TO but this did not generate a higher ratio of horizontal relative to vertical GRF. A change in posture is likely to change the orientation of the center of mass relative to the base of support (22). It is postulated that the HIGH group's greater flexion of the trunk segment relative to the pelvis segment during the WA phase, led to the greater anterior position of the foot relative to the body center of mass at TO and the significant greater peak anterior and change in angular momentum during compared the WA phase compared to the LOW group. Together these may have contributed to their superior field-based assessment performance. Superior agility performance has been associated with greater rotation towards the direction of travel (25), which supports this study's findings of greater trunk rotation range of motion during the R-COD. However, previous research has not observed an associated with lateral trunk flexion during an agility task with superior agility performance (35), a contrast to this study's findings. That is, the HIGH group demonstrating significantly greater lateral flexion angles of the trunk segment relative to the pelvis segment at times of the F_{WA} and F_{V2} away from the new direction of travel in comparison with the LOW group. This greater lateral trunk flexion lead to a more greater peak mediolateral angular momentum away from the direction of travel during the WA phase but could not be explained by between-group differences in lateral foot placement relative to the center of mass at IC or TO. In addition, a significantly more neutral forefoot adduction-abduction position at IC displayed by the HIGH group enables the athlete to respond to the environmental demands of an unanticipated direction of the COD and contributed to the neutral mediolateral angular momentum at IC and TO. Together these might have contributed to the faster mIAT time of the HIGH group compared with the LOW group.

Despite significant between-group differences in relative trunk segment to pelvis segment angles throughout the stance phase, there were no significant differences in L5-S1 or T12-L1 joint angles throughout the contact period of the R-COD. Facet joints of the lumbar vertebrae allow less axial rotation compared with the thoracic vertebrae (6), which may in-part explain why no significant differences or substantial effect sizes for L5-S1 joint angles between groups were observed, however, large effect sizes for T12-L1 joint angles between-group differences at T12-L1 joint throughout the contact period of the R-COD were observed. It is these between-group differences in T12-L1 joint angles that most likely contributed to significant trunk relative to pelvis angles throughout the contact period of the R-COD.

Change-of-direction techniques either involving the torso less (37) or greater trunk flexion (10), laterally flexing (11, 20) or rotating and laterally flexing (11) away from the direction change places the athlete at greater risk of anterior cruciate ligament rupture via increasing knee joint moments (11, 20). Nevertheless, despite the HIGH group utilizing greater trunk flexion, lateral trunk flexion and rotation during the R-COD compared with the LOW group, there were no significant between-group differences or moderate of large size effect sizes in peak internal knee adduction, internal or external rotation joint moments. Furthermore, a lack of significant between-group differences in any of the peak joint moments during the contact phase was noted. It should be noted that whilst there was a moderate (L5-S1 right lateral flexion) and large (hip external rotation and T12-L1 left lateral flexion) effect size between-group difference in joint moments, the small change in mean and high 95% CI suggests that this result is unclear and may not be clinically relevant.

A shorter (12, 35) or no difference in foot-ground contact time duration, and higher vertical F_{V1} and F_{V3}, posterior GRF, posterior and anterior GRF impulse (42) has been linked with superior agility performance. Although there were no significant differences evident for any GRF variables during the R-COD, the HIGH group demonstrated substantially moderate to large effect sizes for longer foot-ground time contact duration, higher vertical and large posterior impulse compared with the LOW group. This may explain the superior field-based performances of the HIGH group. The lack of agreement with previous research between shorter contact periods and superior agility performance, may be attributable to the previous studies not controlling the approach speed (12) and/or the effect of task dependence. Nevertheless, this study's results were in agreement with the longer contact time with superior sprinting performance (22), which may have contributed to the longer GRF application and in turn, higher vertical and posterior GRF impulses observed in this study.

Force dissipation strategy can be utilized during landing tasks by employing a larger range of knee flexion range of motion and foot-ground contact time duration to decrease the magnitude of the peak GRFs and loading rates, and in turn potentially lowers the risk of lower limb injury (43). This strategy was observed in the HIGH group who displayed significantly less knee flexion at IC and TO, indicating that they utilized a relatively larger knee joint flexion range of motion in comparison with the LOW group. Not only did this force dissipation strategy utilized by the HIGH group potentially lower risk of a lower limb injury, it may also have contributed to performance enhancement.

Results of this present study support the argument that the trunk mechanics exerts influence on athletic performance, however, the exact mechanism for potentiation of performance in R-COD and team sport performance, is less clear and further investigation is urgently warranted. The core is unlikely to function to optimize performance by limiting trunk motion in all three planes during athletic movement. Instead it enables motion within an optimal range to capitalize on the efficient utilization of the stretch-shortening cycle, and manage postural changes and the orientation of the center of mass relative to the base of support. This enables optimal application of force along the desired vector, thereby maximizing the efficiency of application of propulsive force. Furthermore, limiting trunk motion during walking has been observed in individuals with lower back pain who adopt a protective strategy by utilizing a guarding or splinting behavior through the activation of superficial trunk muscles that increase trunk stiffness (2). From the results of this present study, it is speculated that the LOW group may have activated the superficial core musculature, and adopted a splinting strategy during the execution of the R-COD as a compensatory mechanism for possessing poor trunk control. Whereas the HIGH group may have utilized a more optimal activation of the deep core musculature to enable greater trunk segment relative to pelvis segment range of motion to enhance performance. The conditioning principle of specificity suggests training is most efficient when training replicates performance conditions and criteria**, and core training in athletes should employ ground-based lifts (squats, dead lift and Olympic lifts) (5) due to the higher core muscular activation than core stability ball exercises (33)**. Therefore, based on the results of the present study and the clinical link of splinting behavior with injury, exercises that require increased trunk rigidity and utilize small core range of motion **to increase trunk control** may not optimally prepare athletes for competition. This raises questions regarding current strength and conditioning practices for minimizing trunk motion during agility to optimize agility **or employing ground-based lifts to train the core,** and urgently warrants further research. **To provide further insight into the relationship between core control and performance, researchers should repeat** the current study's experimental protocol with a larger sample size with different skill level, gender, and/or ag**e, with the additional inclusion of body composition data. The cross-sectional design of this current study is a limitation as it is unknown if the difference in trunk control during the R-COD between-groups was an effect of training history or inherent. As previous research has shown that team sport athletes can retrain their trunk mechanics during a COD task (10),**

researchers should investigate if trunk control can also be retrained during a R-COD via technique modification or core retraining employing the 'big 3' exercises, and if retraining trunk control during a R-COD alters athletic performance and/or injury risk. This future research will enable researchers to ascertain if the trunk control is inherent or can be altered by training, and the optimal training method.

PRATICAL APPLICATIONS

The results of this study do not support current recommendation that athletes require minimal trunk range of motion during an agility task to optimize athletic performance. Decreased trunk control **(high trunk range of motion)** during a R-COD may function facilitating superior athletic performance via enabling the storage, transmission, and control of forces across the system while manipulating body posture to maintain spinal stability. This may enable the athlete to orientate the center of mass relative to the base of support to optimize the ratio of horizontal to vertical force vectors and acceleration. Consequently, current strength and conditioning practices utilizing increased trunk control during conditioning drills may not optimally prepare athletes for the demands of competition. **Whilst this study suggesting that trunk control is a vital component of performance, Future research should investigate whether this trunk control is inherent or an effect of training history, and whether the current optimal athletic performance recommendation of decrease trunk motion during R-COD are supported.**

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CAPTIONS

FIGURE 1 McGill protocol core stability endurance test postures for (A) flexion, (B) extension, (C) left side bridge, and (D) right side bridge hold.

FIGURE 2 Normative distribution of the variable the trunk control during stance phase of a reactive change-of-direction task.

FIGURE 3. Mean ± SD of the (A) joint angles (°) and (B) peak net internal joint moments (Nm·kg^{-1}) displaced during a reactive change-of-direction task for participants with HIGH and LOW trunk control.

FIGURE 4. Means ± SD of the (A) peak GRF (relative BW), (B) timing of peak GRF (s), (C) GRF impulse (BW·s), and (D) FV loading rate (BW·s^{-1}), (E) ratio of peak GRF (%), (F) angular momentum (kg·m^{2}·s^{-1}), and (G) location of the foot segment relative to the body center of mass (m) during a reactive change-of-direction task for participants with HIGH and LOW trunk control.

TABLE 1. Mean ± SD of the field-based measures of performance for the HIGH and LOW trunk control groups.

TABLE 2. Statistical results for the joint angles and peak net internal joint moments displaced during a reactive change-of-direction task for participants with HIGH and LOW trunk control.

TABLE 3. Statistical results for the (A) peak GRF, (B) timing of peak GRF, (C) GRF impulse, and (D) FV loading rate, (E) ratio of peak GRF, (F) angular momentum, and (G) location of the foot segment relative to the body center of mass during a reactive change-of-direction task for participants with HIGH and LOW trunk control.

Figure 1

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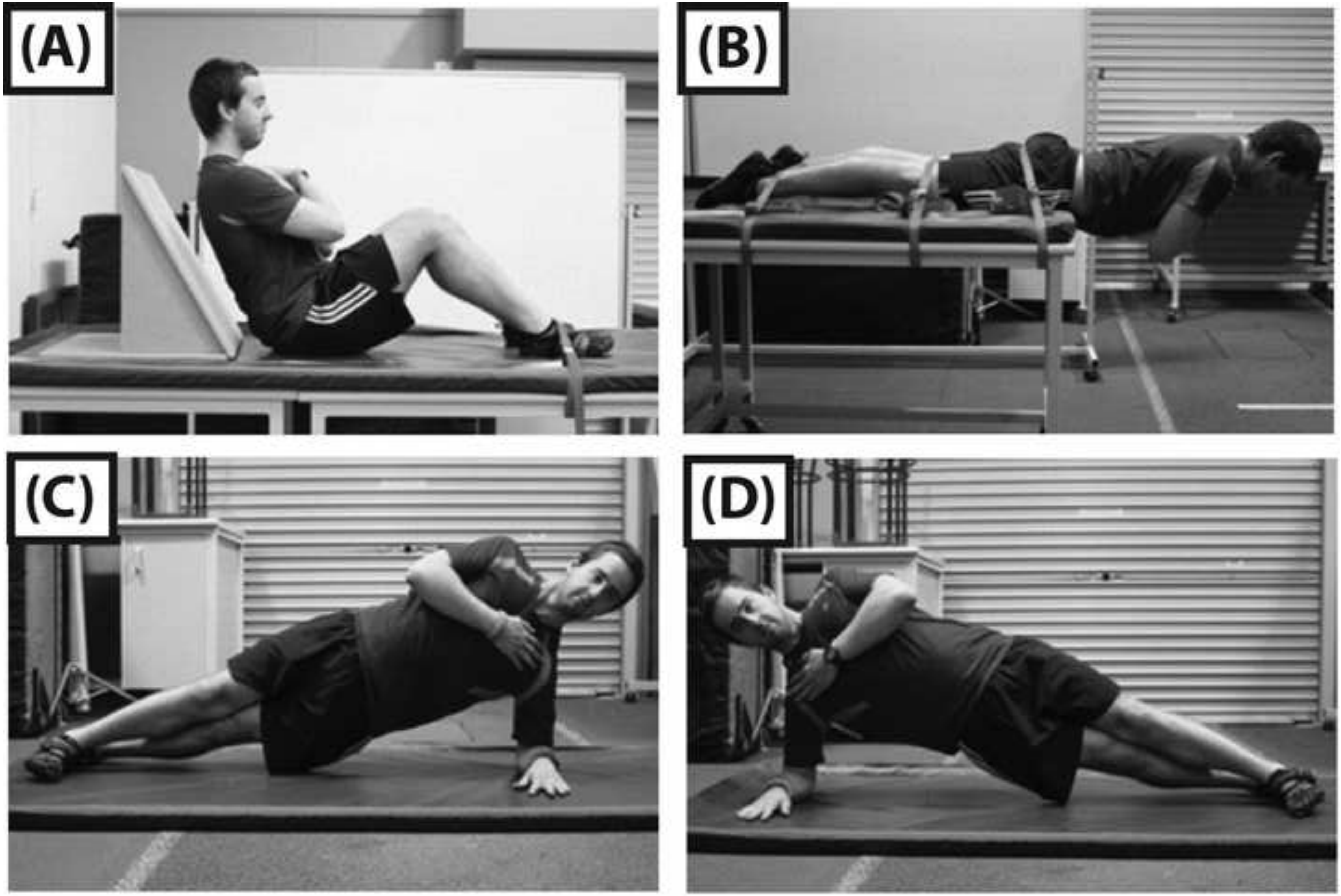

Figure 2

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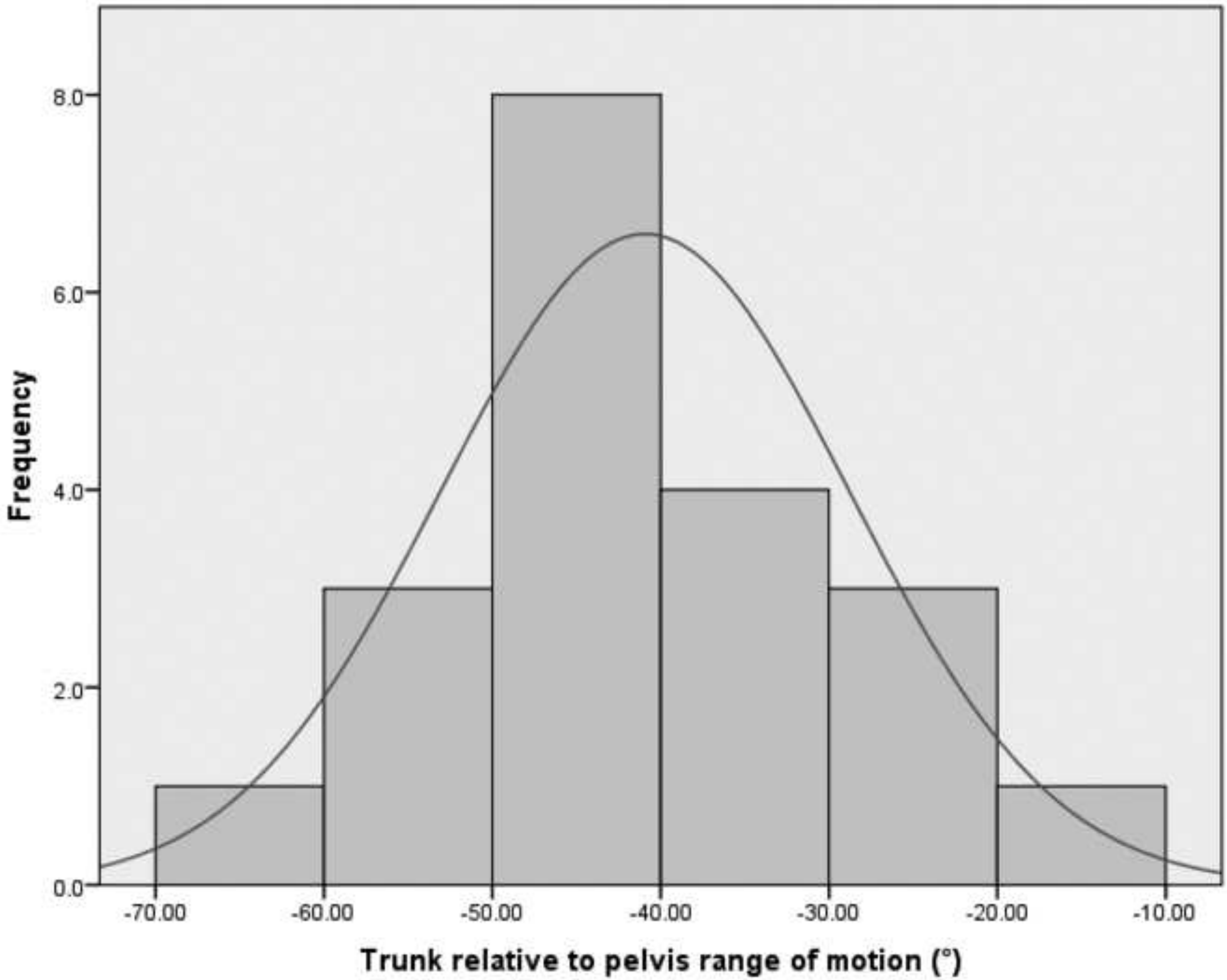

Figure 3

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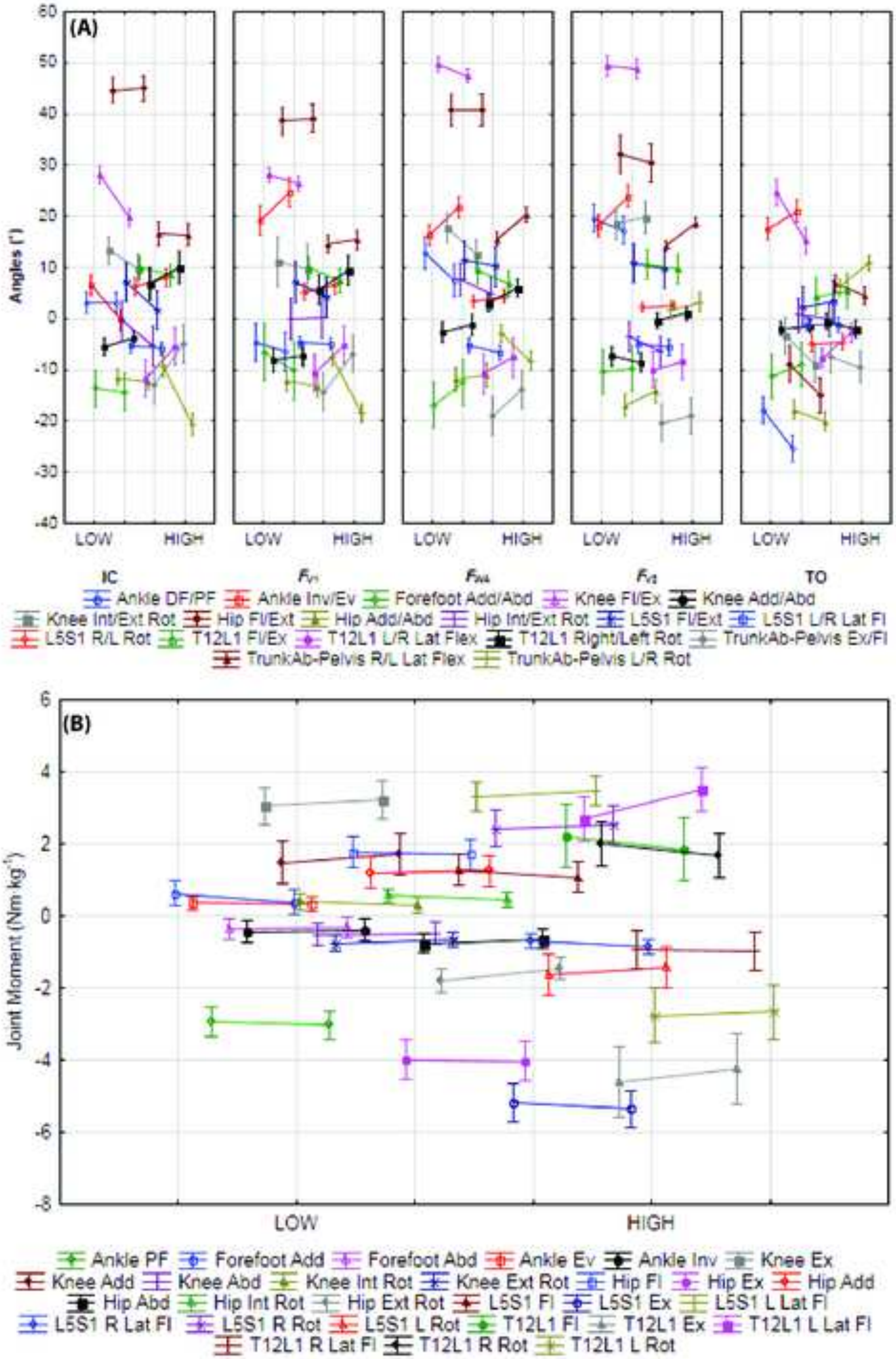

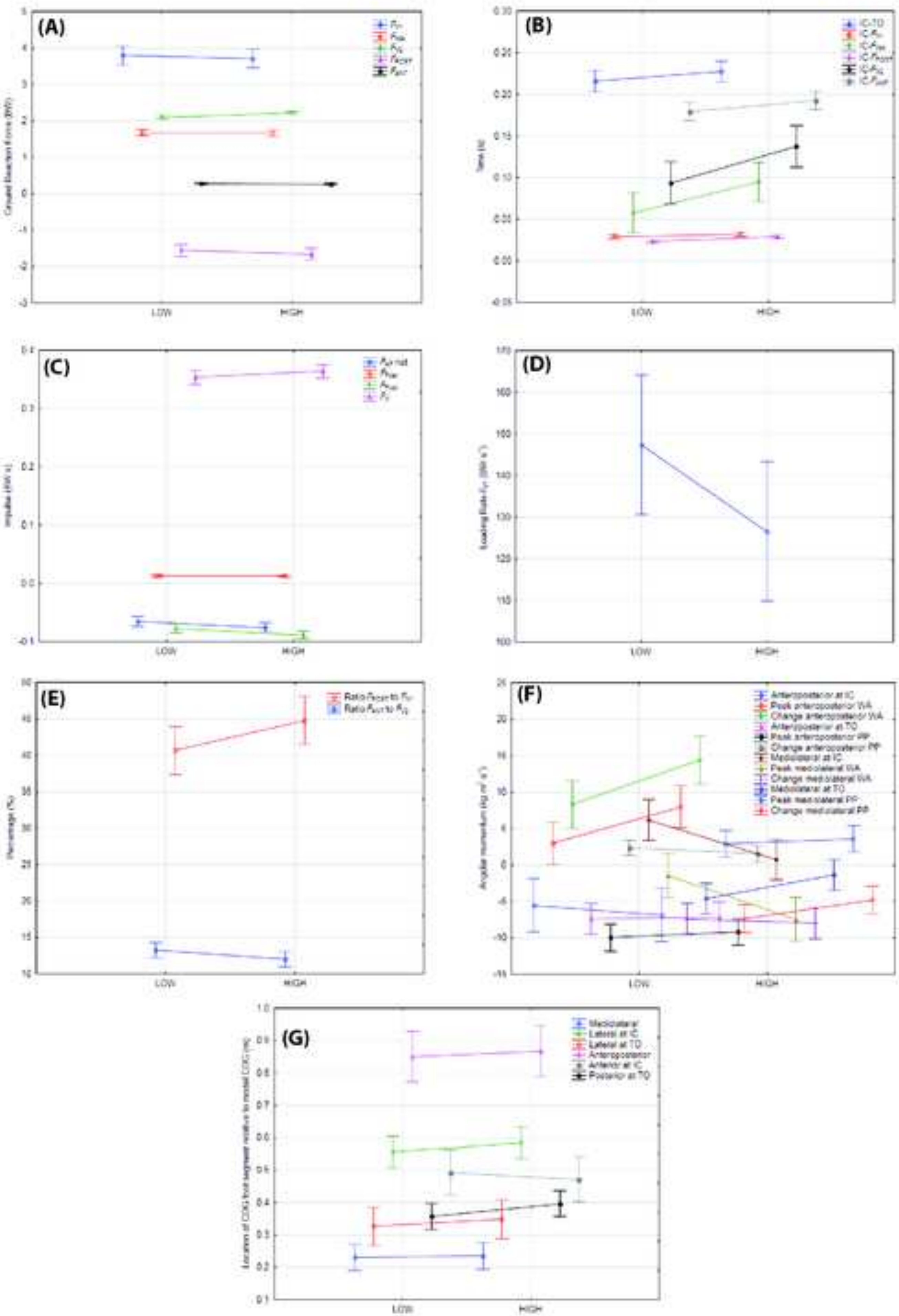

Table 1

Table 1

Variable	LOW	HIGH	d_a	CL	*P*
Age (years)	21.3±1.9	22.1±1.8	0.47	2.1	0.40
Height (cm)	1.84±0.06	1.81±0.05	0.63*	6.4	0.26
Body Mass (kg)	91.4±15.8	87.4±14.3	0.27	17.6	0.63
mIAT (s)	38.9±2.1	36.9±2.9	0.93#	2.9	0.01†
3 RM squat absolute (kg)	100±24	106±29	0.22	32	0.78
3 RM squat relative	1.11±0.26	1.21±0.29	0.36	0.32	0.52
Countermovement jump (cm)	46±8	58±8	1.44#	10	0.02†
McGill Protocol					
Flexion (s)	123±58	168±116	0.77*	107	0.42
Extension (s)	112±41	98±32	0.37	43	0.36
Left Flexion (s)	85±19	89±31	0.25	30	0.62
Right Flexion (s)	89±23	92±34	0.14	34	0.78
Total (s)	409±108	446±181	0.34	174	0.60
Stability evaluation					
1. Firm surface					
Double limb stance (°·s^{-1})	0.67±0.16	0.80±0.39	0.44	0.35	0.44
Tandem stance (°·s^{-1})	1.78±0.88	1.86±0.58	0.10	0.87	0.86
Single limb stance(°·s^{-1})	1.27±0.38	1.40±0.46	0.31	0.49	0.58
2. Foam surface					
Double limb stance (°·s^{-1})	1.83±0.53	1.99±0.40	0.34	0.55	0.54
Tandem stance (°·s^{-1})	3.50±0.63	3.53±0.91	0.04	0.91	0.95
Single limb stance (°·s^{-1})	3.74±1.60	3.86±1.31	0.08	1.70	0.89
Limits of stability					
1. Forward					
Maximum excursion (%)	98±7	90±10	0.84#	10	0.12
End point excursion (%)	85±13	72±17	0.86#	17	0.11
Velocity (°·s^{-1})	3.7±1.6	4.6±1.6	0.58*	1.9	0.29
2. Diagonal (forward/dominant side)					
Maximum excursion (%)	106±4	100±12	0.70*	11	0.20
End point excursion (%)	93±12	89±16	0.31	16	0.58
Velocity (°·s^{-1})	8.7±4.2	8.2±3.6	0.14	4.6	0.80
3. Dominant side					
Maximum excursion (%)	97±6	94±9	0.38	8.9	0.50
End point excursion (%)	79±15	79±15	0.02	17	0.97
Velocity (°·s^{-1})	7.9±4.1	8.1±2.9	0.05	4.1	0.93
4. Diagonal (backward/dominant side)					
Maximum excursion (%)	95±12	101±7	0.67*	11	0.22
End point excursion (%)	83±20	92±13	0.53*	19	0.34
Velocity (°·s^{-1})	5.0±1.8	8.1±1.9	1.30#	2.2	0.01†
5. Backward					
Maximum excursion (%)	91±10	77±14	1.00#	14.3	0.06
End point excursion (%)	69±19	64±22	0.28	24	0.62
Velocity (°·s^{-1})	4.7±2.3	4.5±2.1	0.11	2.6	0.84
6. Diagonal (backward/non-dominant side)					
Maximum excursion (%)	94±9	96±7	0.18	10	0.75
End point excursion (%)	86±15	90±11	0.29	15	0.61
Velocity (°·s^{-1})	7.3±3.0	6.9±2.1	0.16	3.0	0.77
7. Non-dominant side					
Maximum excursion (%)	96±5	96±8	0.02	8	0.97
End point excursion (%)	86±8	74±4	1.40#	7	0.01†
Velocity (°·s^{-1})	9.2±4.3	7.5±2.3	0.48	4	0.39
8. Diagonal (forward/non-dominant side)					
Maximum excursion (%)	106±9	103±6	0.36	9	0.53
End point excursion (%)	96±13	86±17	0.64*	18	0.25
Velocity (°·s^{-1})	9.3±3.9	6.4±2.5	0.82#	3.8	0.13

Modified Illinois Agility Test (mIAT), 3 repetition back squat (3RM Squat), 95% confidence limit (CL) defines the range representing the uncertainty in the true value of the (unknown) population mean.

d_a effect size

* indicates moderate between-group condition difference in the effect size (value 0.50–0.79)

# indicates large between-group condition difference in the effect size (value ≥0.80)

† indicates a significant between-group difference, $P < 0.05$

Table 2

Table 1

Joint angles (°)	IC			F_{V1}			F_{WA}			F_{V2}			TO		
	d^a	CL	*P*	d^a	CL	*P*	d^a	CL	*P*	d^a	CL	*P*	d^a	CL	*P*
Ankle dorsi-plantar flexion	0.01	5.9	0.98	0.18	11.6	0.75	0.63*	9.9	0.25	0.33	8.6	0.56	0.99#	7.8	0.06
Forefoot adduction-abduction	1.04#	6.5	0.05†	0.68*	9.1	0.22	0.91#	6.3	0.09	0.91#	6.8	0.09	0.59*	6.7	0.29
Ankle eversion-inversion	0.08	11.1	0.89	0.26	17.2	0.65	0.38	13.7	0.50	0.06	13.4	0.92	0.21	13.3	0.72
Knee flexion-extension	1.75#	5.3	0.00†	0.40	4.5	0.45	0.60*	4.3	0.28	0.12	6.6	0.84	1.14#	17.8	0.03†
Knee adduction-adduction	0.29	5.1	0.52	0.20	6.9	0.75	0.30	6.0	0.60	0.26	6.7	0.65	0.15	3.5	0.79
Knee internal rotation	0.44	8.2	0.37	0.12	15.0	0.84	0.66*	9.0	0.23	0.17	8.2	0.77	0.56*	16.9	0.31
Hip flexion-extension	0.07	7.5	0.91	0.05	8.4	0.93	0.00	9.9	1.00	0.17	11.6	0.76	0.64*	10.9	0.25
Hip adduction-abduction	0.21	4.8	0.72	0.22	5.8	0.70	0.17	7.0	0.77	0.49	6.8	0.38	0.45	5.9	0.43
Hip internal-external rotation	0.47	12.2	0.40	0.02	12.5	0.97	0.35	9.8	0.54	0.39	8.7	0.49	0.10	10.1	0.86
L5S1 flexion-external	0.54*	11.6	0.33	0.30	12.0	0.60	0.13	11.6	0.82	0.12	11.7	0.83	0.11	12.2	0.85
L5S1 left-right lateral flexion	0.14	4.0	0.80	0.16	3.6	0.77	0.35	4.7	0.54	0.14	5.0	0.81	0.02	4.3	0.97
L5S1 right-left rotation	0.39	5.3	0.49	0.30	4.9	0.60	0.30	3.7	0.60	0.13	2.9	0.81	0.05	4.9	0.93
T12L1 flexion-extension	0.27	6.6	0.63	0.41	7.0	0.47	0.40	8.0	0.48	0.11	8.9	0.85	0.11	10.8	0.84
T12L1 left-right lateral flexion	0.64*	11.1	0.24	0.58*	10.9	0.30	0.32	12.0	0.57	0.19	10.8	0.74	0.94#	5.5	0.08
T12L1 right-left rotation	0.39*	9.7	0.49	0.51*	8.6	0.37	0.65*	5.1	0.24	0.36	4.4	0.53	0.35	5.0	0.53
TrunkPelvis flexion-extension	0.78*	11.6	0.15	0.77*	10.8	0.16	0.54*	11.3	0.33	0.15	11.0	0.80	0.24	9.2	0.67
TrunkPelvis left-right lateral flexion	0.03	6.9	0.96	0.15	5.7	0.79	1.09#	4.3	0.03†	1.31#	3.0	0.01†	0.51*	5.2	0.36
TrunkPelvis right-left rotation	1.42#	6.6	0.00†	1.50#	5.5	0.00†	0.98#	5.7	0.06	0.33	5.5	0.56	1.04#	4.6	0.05†

Joint moment (Nm·kg^{-1})	d^a	CL	*P*
Ankle plantarflexion	0.22	1.09	0.70
Forefoot adduction	0.59*	0.91	0.29
Forefoot abduction	0.12	0.98	0.83
Ankle inversion	0.09	0.99	0.87
Ankle eversion	0.12	0.98	0.84
Knee extension	0.29	1.33	0.61
Knee adduction	0.33	1.13	0.56
Knee abduction	0.14	1.20	0.80
Knee internal rotation	0.36	0.99	0.53
Knee external rotation	0.47	0.96	0.40
Hip flexion	0.14	1.14	0.81
Hip extension	0.05	1.35	0.93
Hip adduction	0.12	1.34	0.84
Hip abduction	0.36	1.20	0.53
Hip internal rotation	0.49	0.96	0.38
Hip external rotation	0.82#	0.92	0.13
L5S1 flexion	0.41	2.09	0.47
L5S1 extension	0.29	0.87	0.61
L5S1 left lateral flexion	0.36	1.27	0.53
L5S1 right lateral flexion	0.65*	1.30	0.24
L5S1 right rotation	0.19	0.97	0.74
L5S1 left rotation	0.30	1.48	0.60
T12L1 flexion	0.34	1.16	0.54
T12L1 extension	0.33	0.87	0.56
T12L1 left lateral flexion	0.96#	1.42	0.07
T12L1 right lateral flexion	0.06	1.27	0.91
T12L1 right rotation	0.44	1.11	0.43
T12L1 left rotation	0.12	1.79	0.83

Initial foot-ground contact (IC), first peak vertical ground reaction force (F_{V1}), first local minimum of the vertical ground reaction force after F_V (F_{WA}), second peak vertical ground reaction force (F_{V2}), take-off (TO) and 95% confidence limit (CL) defines the range representing the uncertainty in the true value of the (unknown) population mean.
For the above rotations: ankle dorsiflexion, forefoot adduction, ankle eversion, knee flexion, knee adduction, knee internal rotation, hip flexion, hip adduction, hip internal rotation, L5-S1 flexion, L5-S1 left lateral flexion, L5-S1 right rotation, T12-L1 flexion, T12-L1 left lateral flexion, and T12-L1 right rotation are positive.
d_a effect size
* indicates moderate between-group condition difference in the effect size (value 0.50–0.79)
\# indicates large between-group condition difference in the effect size (value ≥0.80)
† indicates a significant between-group condition difference, $P < 0.05$

Table 3

Table

Variable	d_a	CL	*P*	Variable	d_a	CL	*P*
Force				***Location of COG foot segment relative to model*** **COG**			
F_{V1} (BW)	0.11	0.8	0.83	Mediolateral displacement	0.11	5.7	0.85
F_{WA} (BW)	0.08	0.3	0.87	Lateral displacement at IC	0.46	7.0	0.41
F_{V2} (BW)	0.77	0.1	0.08	Lateral displacement at TO	0.32	8.4	0.58
F_{POST} (BW)	0.23	0.5	0.69	Anteroposterior	0.20	11.1	0.73
F_{ANT} (BW)	0.26	0.1	0.76	Posterior location at IC	0.27	9.8	0.64
LR F_{V1} (BW·s^{-1})	0.41	52	0.45	Anterior location at TO	0.77*	5.88	0.16
IC-F_{V1} (ms)	0.41	8	0.43	***Angular momentum***			
IC-F_{WA} (ms)	3.18#	73	0.34	Anteroposterior at IC	0.31	1.01	0.58
IC-F_{V2} (ms)	2.34#	78	0.31	Peak anteroposterior WA	1.17#	1.24	0.02†
IC-TO (ms)	0.27	39	0.59	Change anteroposterior WA	1.23#	1.01	0.01†
IC-F_{POST} (ms)	1.24#	6	0.11	Anteroposterior at TO	0.05	1.20	0.93
IC-F_{ANT} (ms)	0.37	33	0.37	Peak anteroposterior PP	0.39	1.35	0.49
F_V impulse (BW·s)	0.63	0.04	0.34	Change anteroposterior PP	0.60*	1.13	0.28
F_{Post} impulse (BW·s)	0.86#	0.02	0.13	Mediolateral at IC	1.27#	0.90	0.01†
F_{Ant} impulse (BW·s)	0.39	0.01	0.39	Peak mediolateral WA	1.27#	1.10	0.01†
F_{AP} net impulse (BW·s)	0.80#	0.03	0.13	Change mediolateral WA	0.21	1.41	0.71
Ratio F_{POST} to F_{V1} (%)	0.48	10	0.39	Mediolateral at TO	1.09#	0.99	0.03†
Ratio F_{ANT} to F_{V2} (%)	0.45	3	0.42	Peak mediolateral PP	0.30	1.02	0.60
				Change mediolateral PP	1.00#	1.03	0.06

First peak vertical ground reaction force after Initial foot-ground contact (F_{V1}), first local minimum of vertical ground reaction force after IC (F_{WA}), second peak vertical ground reaction force after Initial foot-ground contact (F_{V2}), peak posterior ground reaction forces (F_{POST}), peak anterior ground reaction force (F_{ANT}), loading rate of the F_{V1} (LR F_{V1}), time interval between initial foot-ground contact (IC) to the time of the F_{V1} (IC-F_{V1}), time interval between IC to the time of the F_{WA} (IC-F_{WA}), time interval between IC to the time of the F_{V2} (IC-F_{V2}), time interval between IC to the time of the toe-off (IC-TO), time interval between IC to the time of the F_{POST} (IC-F_{POST}), and time interval between IC to the time of the F_{ANT} (IC-$_{FANT}$), vertical ground reaction force impulse (F_V impulse), posterior ground reaction force impulse (F_P impulse), anterior ground reaction force impulse (F_A impulse), anterior posterior net force impulse (F_{AP} net impulse), and
95% confidence limit (CL) defines the range representing the uncertainty in the true value of the (unknown) population mean.
d_a indicates effect size.
* Indicates moderate between-group difference in the effect size for a value between 0.50–0.79.
# Indicates large between-group difference in the effect size for a value greater than 0.80.† indicates a significant between-group condition difference, $P < 0.05$