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## Adding a weight to constrain the trunk increases knee joint kinetics during sidestep cutting in female athletes

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Sidestep cutting exposes the knee to high multiplanar loads that both challenge tissue capacity and provide an opportunity to develop resilience through progressive exposure. This study investigated task constraints applied at the trunk and preparatory step and changes in lower-body joint kinetics associated with ACL injury risk during sidestepping in female athletes. Twenty-one trained female athletes performed six sidestep conditions: pre-planned and unplanned sidesteps, each with and without trunk (holding ~5–7.5% body mass at chest level) and preparatory-step (ducking under an adjustable rope at eye height) constraints. Relative joint power at the hip, knee, and ankle was analysed using statistical parametric mapping. In pre-planned sidesteps, trunk constraints significantly increased energy absorption at the knee during early stance (23–27%,  $p < 0.001$ ). Preparatory-step constraints did not alter energy absorption at the knee but significantly increased energy generation at the hip relative to trunk-constrained and unconstrained conditions between 23 and 35% of stance ( $p < 0.001$ ). Unplanned sidesteps showed no kinetic differences among conditions. Implementing trunk constraints during pre-planned sidesteps increases mechanical demands on the knee joint, suggesting these conditions may serve as a useful means to progressively expose athletes to higher joint loads in controlled training environments. These findings inform practical training strategies to increase tissue capacity and prepare female athletes for high-risk sidestepping scenarios, potentially contributing to an increased injury resiliency.

**Keywords** ACL, Biomechanics, Training, Task constraints, Joint power, Ecological dynamics

Non-contact anterior cruciate ligament (ACL) injuries during sidestep cutting maneuvers typically occur within the first 50 ms after initial contact when the imposed mechanical demands exceed the tissue capacities<sup>1,2</sup>. Combined externally applied knee flexion, valgus and internal rotation moments can elevate ACL strain up to the point of tissue failure<sup>3,4</sup>. The mechanical knee joint demands are well documented, demonstrating how joint kinematics affect externally applied knee joint moments<sup>5–7</sup>. Factors such as single joint alignments (e.g., knee flexion during initial contact, lateral trunk sway, hip abduction)<sup>5,8,9</sup> and entry velocity<sup>10</sup> can increase knee joint moments during sidesteps. These insights have subsequently been used to inform training interventions aiming to reduce ACL injury risk by recommending to minimise or avoid these specific joint angles when sidestepping<sup>8,11–14</sup>. However, despite extensive research, ACL injuries are not declining<sup>15</sup>, questioning whether avoiding specific high-risk movements sufficiently prepares athletes, especially considering that such compromised positions can arise in the context of complex in-game scenarios. In other words, increasing an athlete's load tolerance during high-impact activities (e.g., sidesteps with suboptimal body positions) and preparing them for such “worst-case” scenarios may be more effective for reducing ACL injury risk<sup>16</sup>.

Traditionally, knee joint moments have served as primary measures to infer ACL loading and subsequent injury risk during sidestepping tasks. However, relying exclusively on isolated plane-specific moments neglects the interdependency of multiplanar loading conditions and disregards the critical factor of load application rate. Forces applied predominantly in one plane inevitably produce secondary rotations and translations due to the knee's complex articular geometry and tibiofemoral asymmetry. Consequently, identical peak valgus

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moments can yield markedly different ACL strains depending on accompanying flexion angles and moments. Evaluating joint moments alone also disregards the rate of loading - an essential determinant of ligamentous injury established in materials science and tissue biomechanics<sup>17,18</sup>. Joint power, defined as the product of joint moments and angular velocities, inherently accounts for both the magnitude and rate of mechanical energy absorption (negative power) or generation (positive power) by surrounding structures. Recent evidence links reduced energy absorption or excessive joint power to increased lower-limb injury risk<sup>19,20</sup>. As such, joint power analyses afford additional and complementary biomechanical insights, potentially overcoming critical limitations inherent in isolated joint moment assessments and facilitating interpretation between condition differences<sup>21–24</sup>.

Resistance training enhances muscular strength and tissue integrity, improving the ability to handle mechanical demands during high-impact activities<sup>25–27</sup>. However, access and opportunity to dedicated and supervised resistance training are often limited, especially outside of male professional sports. Therefore, alternative training methods that practitioners can implement during on-field sessions may provide an alternative approach to increasing injury resiliency and robustness. An emerging approach based on dynamical systems theory is to manipulate constraints (i.e. organism, task and environment) to change the execution strategy to provide a mechanical overload<sup>28–31</sup>. For example, changing the execution strategy with task constraints alters joint kinetics during vertical jumping<sup>32</sup>, sprinting<sup>33</sup> and isometric mid-thigh pulls<sup>34</sup>, thus changing the strain on certain muscle groups and joint structures. Although most prior work has focused on joint moments, several studies have demonstrated that changes in energy absorption, joint work, and joint power provide complementary insight into how athletes manage mechanical loading during dynamic movements such as landing and cutting<sup>19,20,35</sup>. How such energetic responses are influenced by manipulating task constraints remains largely unexplored. Integrating joint energetics with a constraints-based framework may therefore offer new insight into how altering movement strategies affects mechanical loading and energy distribution across the lower limbs.

During sidestep cutting, trunk positioning, particularly increased transverse and frontal plane trunk rotation opposite to the cutting direction, and reacting to external stimuli (e.g., a generic visual cue or opponent movement), elevate multiplanar knee joint moments<sup>5,36,37</sup>. Deliberately manipulating these factors through external constraints could intentionally alter athlete execution strategy, influencing both joint kinematics and kinetics. Such targeted constraints could promote specific mechanical adaptations by redistributing joint loading patterns or increasing mechanical demand at selected joints, potentially facilitating soft tissue adaptation and increasing tissue resiliency in the long term<sup>16</sup>. For example, constraints designed to lower an athlete's center of mass (COM) during the penultimate step, prior to sidestep execution, may encourage athletes to increase sagittal plane hip and knee flexion. Observable kinematic changes to specific constraints compared to unconstrained task execution may shift eccentric load absorption away from the knee and towards the larger hip musculature during the early stance. Such redistribution could reduce excessive mechanical demands placed directly upon knee joint structures, including the ACL, during early stance periods when sidestepping.

Conversely, intentionally disrupting trunk control by imposing a task constraint (e.g., holding an external weight of approximately 5–7.5% body mass at chest level during sidestepping) aims to increase mechanical demand at the knee during early stance in sidestep cutting by altering trunk stability and upper-body posture<sup>38</sup>. This constraint aims to modify overall execution strategy, providing a controlled means of altering joint loading without prescribing a specific kinematic technique. Although higher knee loading is typically considered a risk factor, mechanical loading also stimulates collagen remodeling and increases tissue capacity when progressed appropriately<sup>17,18</sup>. In fact, the human ACL undergoes hypertrophy, or volume increases with repeated loading<sup>39,40</sup>, indicating that ligamentous tissue can adapt to elevated mechanical stress. Accordingly, controlled and progressive overload may help develop the capacity to tolerate the high-demand postures encountered during sidestepping.

Critically, constraints-induced modifications in sidestepping mechanics can vary considerably among athletes, resulting in multiple viable execution strategies<sup>5</sup>. Therefore, explicitly examining the changes in kinetics under these constraints is necessary to better understand their practical utility in training settings. We aim to quantify how imposed constraints affect lower-body joint kinetics associated with ACL injury risk during sidestepping tasks. Thus, the primary objective of this study was to examine trunk and penultimate-step constraints and subsequent changes in lower-body joint kinetics compared to unconstrained sidesteps, during both pre-planned and unplanned sidestep cutting. We hypothesised that: (1) imposing a trunk constraint (external weight held at chest level) would increase the mechanical demands on the knee joint, reflected by greater energy absorption at the knee; and (2) applying a penultimate-step constraint (ducking under an adjustable rope during the penultimate step) would lower knee joint demands while increasing hip joint eccentric demands relative to unconstrained conditions. We additionally hypothesised that the effects of trunk and preparatory-step constraints on joint kinetics would be similar across pre-planned and unplanned sidestep cutting, thereby testing whether these manipulations generalise across different task contexts.

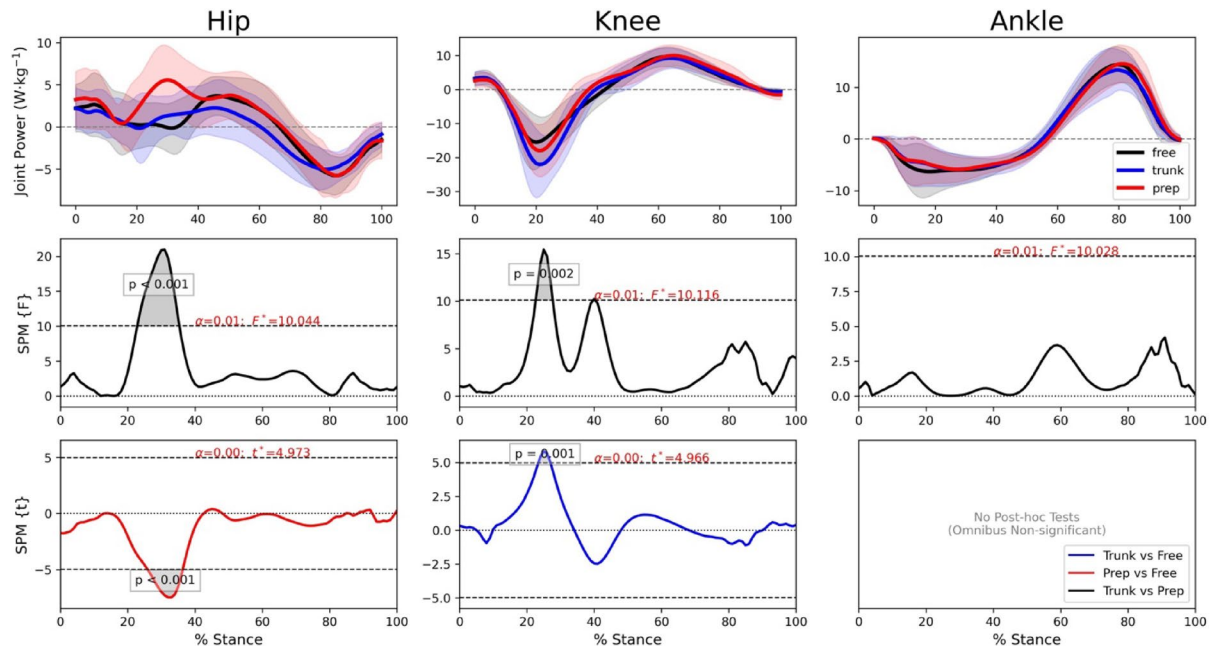
## Results

A significant main effect for condition on sidestep angle ( $F(5, 23.59) = 3.32, p = 0.02$ ) and entry velocity ( $F(5, 19.9) = 33.3, p < 0.001$ ) was found. *Post hoc* analyses showed sidestep angle was lower for PP compared to UP<sub>trunk</sub> ( $p = 0.03; d = 0.73$  [95% CI = 0.36–1.09]). The horizontal velocity of the COM and initial contact ( $V@IC$ ) was significantly higher in all pre-planned compared to all unplanned conditions by  $0.67\text{--}0.9\text{ m}\cdot\text{s}^{-1}$  ( $p < 0.001; d > 2.2$ ), with no significant differences among pre-planned ( $p > 0.28$ ) and unplanned conditions ( $p = 1.00$ ) (Table 1).

The time-normalised mean and SD for net hip, knee, and ankle joint power ( $\text{W}\cdot\text{kg}^{-1}$ ) across the stance phase are depicted in Fig. 1 (top panel). SPM repeated-measures ANOVA revealed significant differences among pre-

Condition	Sidestep angle (°)	V@IC (m·s <sup>-1</sup> )
PP <sub>free</sub>	38.1 ± 4.5	3.46 ± 0.30 <sup># †</sup>
PP <sub>trunk</sub>	38.3 ± 4.6	3.54 ± 0.37 <sup># †</sup>
PP <sub>prep</sub>	37.6 ± 4.6 <sup>*</sup>	3.65 ± 0.48 <sup># †</sup>
UP <sub>free</sub>	40.3 ± 5.8	2.78 ± 0.25
UP <sub>trunk</sub>	40.9 ± 4.7	2.79 ± 0.28
UP <sub>prep</sub>	39.5 ± 6.3	2.75 ± 0.28

**Table 1.** Sidestepping kinematics. Data are presented as mean ± SD. <sup>#</sup> = significant difference compared to UP<sub>free</sub> ( $p < 0.001$ ); <sup>\*</sup> = significant difference compared to UP<sub>trunk</sub> ( $p < 0.001$ ); <sup>†</sup> = significant difference compared to UP<sub>prep</sub> ( $p < 0.001$ ); V@IC = horizontal velocity of the COM at initial contact. COM = Center of mass.



**Fig. 1.** Top panel - Mean and SD time series for the hip, knee and ankle joint power normalised to body mass. Middle panel - SPM repeated measures ANOVA results for all pre-planned conditions. Inference curves with suprathreshold clusters (shaded) with the critical threshold (dashed line). Bottom panel - Follow-up SPM T-test with Bonferroni correction between only the significant pre-planned conditions. Inference curves with suprathreshold clusters (shaded) and critical threshold (dashed line). ANOVA = analysis of variance; SPM = statistical parametric mapping.

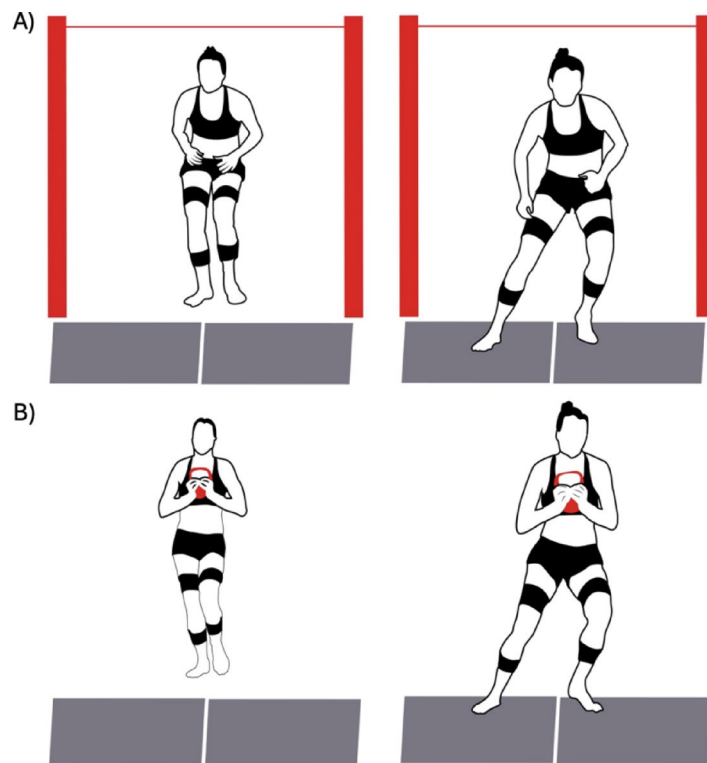
planned conditions for hip joint power ( $JP_{HIP}$ ) between 23 and 35% of stance ( $\{F\}=10.044$ ,  $p < 0.001$ ) and for knee joint power ( $JP_{KNEE}$ ) between 23 and 27% ( $\{F\}=10.116$ ,  $p < 0.001$ ) (Fig. 1 - middle panel). No significant differences in ankle joint power ( $JP_{ANKLE}$ ) or between any conditions during unplanned sidesteps were detected (Online Supplement Fig. 1).

Post-hoc pairwise contrasts demonstrated significant differences during early stance (Fig. 1 - bottom panel). The PP<sub>prep</sub> condition elicited significantly greater positive  $JP_{HIP}$  values compared to PP<sub>free</sub> (21–38%,  $\{t\}=4.973$ ,  $p < 0.001$ ). However, no significant differences emerged between PP<sub>free</sub> and PP<sub>trunk</sub> or between PP<sub>trunk</sub> and PP<sub>prep</sub> for hip joint power ( $JP_{HIP}$ ) after the Bonferroni correction. For knee joint power, the PP<sub>trunk</sub> condition showed significantly greater negative knee joint power ( $JP_{KNEE}$ ) compared to PP<sub>free</sub> from 23 to 27% stance ( $\{t\}=4.966$ ,  $p < 0.001$ ). No other significant pairwise differences emerged in the knee joint power post-hoc analyses after correction.

Exploratory analyses of resultant and decomposed knee joint moments (Online Supplementary) indicated that the trunk-constraint condition produced a temporally aligned increase in resultant knee moment between 24 and 33% of stance, coinciding with the period of heightened knee energy absorption. Full moment waveforms are presented in the Online Supplement Figs. 2–5.

## Discussion

The study investigated how task constraints affect lower-body joint kinetics associated with mechanical demands relevant to ACL injury risk during early stance in pre-planned and unplanned sidesteps in female athletes.



**Fig. 2.** (A) Visual representation of the preparatory step constraint and (B) trunk constraint (bottom panel) during the preparatory steps (left column) and execution step (right column). The red highlights indicate the constraints.

Our first hypothesis was partially supported with the pre-planned & trunk constrained condition ( $PP_{trunk}$ ) significantly increased energy absorption at the knee ( $JP_{KNEE}$ ) during early stance (23–27%,  $p < 0.001$ ) compared to pre-planned & unconstrained condition ( $PP_{free}$ ) (Fig. 1). Contrary to our initial hypothesis, the pre-planned & preparatory step constrained condition ( $PP_{prep}$ ) failed to decrease energy absorption at the knee. Instead, energy generation at the hip increased during early stance compared to the pre-planned & unconstrained condition ( $PP_{free}$ ) (21–38%,  $p < 0.001$ ). Our final hypothesis was rejected as no differences were observed among unplanned conditions. Together, these findings indicate that trunk constraints ( $PP_{trunk}$ ) elevate knee demand in pre-planned sidesteps, whereas preparatory-step constraints ( $PP_{prep}$ ) increase energy generation at hip. These findings can inform training interventions to overload the knee surrounding musculature and structures during early stance through controlled and progressive exposure and prepare athletes for high-impact sidestepping demands.

The observed increase in energy absorption at the knee during pre-planned sidesteps with trunk constraints supports our hypothesis that holding an external mass (~ 5–7.5% of body mass) at chest level elevates mechanical demand at the knee. This finding aligns with existing literature showing altered trunk loading conditions, such as holding sports equipment, and elevating knee joint moments<sup>38</sup>. Although we did not explicitly quantify trunk kinematics, mechanically, adding mass at the trunk will likely shift the body's centre of mass superiorly and anteriorly, thereby altering ground reaction force orientation relative to the knee joint centre and increasing energy absorption at the knee. These results highlight the influence of trunk control on lower-limb mechanical demands and the potential of such constraints to provide a controlled and progressive overload stimulus for knee-extensor and stabilising structures<sup>5,36,41</sup>. These findings reinforce the importance of enhancing athletes' ability to tolerate imposing demands through targeted resistance, plyometric training and methods to increase trunk capacity (i.e., muscular strength) and facilitate dynamic control when sidestepping (i.e., the ability to control the trunk in different execution strategies)<sup>14,27,36</sup>.

Contrary to our hypothesis, implementing a constraint designed to implicitly lower the center of mass (COM) prior to sidestepping did not increase energy absorption at the hip. Instead, it resulted in increased energy generation at the hip during early stance, indicating a redistribution of mechanical demand toward the hip musculature. This pattern suggests that athletes accommodated the preparatory-step constraint by increasing hip contribution to propulsion rather than by modifying knee energy absorption. The finding highlights the complexity of manipulating movement strategies through task constraints, as altering one segment's mechanics can lead to compensatory adjustments elsewhere in the kinetic chain. Nevertheless, such constraint-driven changes in joint energetics provide valuable insight into how specific task conditions can target different muscular and joint demands, informing future strategies aimed at progressively developing load tolerance across the lower limbs.

The constraints failed to alter energy absorption or generation at any lower-limb joints during unplanned sidesteps. This limited change likely reflects the significantly lower entry velocity compared to the pre-planned conditions. Given that higher travel velocities increase mechanical demands around the knee joint<sup>10</sup>, sidestepping with a reduced entry velocity seems ineffective in imposing mechanical overload<sup>42</sup>. As such, holding an external mass in front of the chest when sidestepping may not increase knee joint demands until the athlete reaches a certain horizontal velocity at initial contact.

Contrary to previous research, unplanned conditions failed to increase mechanical knee joint demands compared to pre-planned conditions<sup>12,37,43,44</sup>. Although approach velocity was standardised up to 2 m before the targeted sidestepping area, participants likely decelerated to a greater extent during the step(s) prior to sidestepping in unplanned conditions to allow enough time to perceive the generic stimulus and react accordingly. The magnitude of deceleration might reflect the participants' perceived ability to tolerate the imposing mechanical demands nested in the affordance-based control framework<sup>45,46</sup>. This framework proposes that skilled performance necessitates that individuals' motor capacities (e.g., muscle strength) are scaled or calibrated relative to the task and environment<sup>45</sup>. Hence, insufficient capacity may limit the ability to execute desired movements (e.g., sidestepping at high velocities) and compromise performance<sup>47–49</sup>, reinforcing the need to develop both the physical capacity (i.e. with resistance and plyometric training) and the ability to efficiently utilise this capacity when sidestepping (i.e. with skill training)<sup>50–52</sup>. Understanding this trade-off-like behaviour between entry velocity and the mechanical demands around isolated lower-limb joints is crucial when aiming to overload certain structures and plan design training sessions<sup>10</sup>.

Exploratory resultant moment analyses showed a temporally aligned increase in knee loading during the same early-stance period (24–33% of stance and [ $p=0.002$ ]) in which knee energy absorption increased under trunk loading (Online Supplement Fig. 1). This alignment adds mechanical context but does not alter our primary interpretation, as joint power remained the prespecified and theoretically grounded outcome. In the context of these findings, joint power analyses emerge as particularly informative, explicitly incorporating the temporal component of load application rates. Resultant joint power metrics provide valuable insight into dynamic sports movements by quantifying energy generated or absorbed at distinct joints, a perspective often missing from isolated joint moment analyses<sup>53</sup>. However, because resultant joint power is a scalar quantity, complementary assessment of joint moments can help contextualise multiplanar loading characteristics. Collectively, these exploratory analyses highlight the complementary nature of joint powers and moments and suggest avenues for future work using musculoskeletal modelling to further clarify how external joint kinetics relate to ACL strain.

Despite the potential benefits discussed in this research, the current study is not without limitations. First, our cohort was limited to female Australian Rules Football players, restricting the generalisability of findings to other sports and populations. Next, we focused exclusively on the dominant leg for sidestepping, leaving questions about whether non-dominant leg mechanics might differ. Further, in the current biomechanical model, we assigned the load for the trunk-constrained conditions to the participant's mass instead of the isolated trunk segment. This simplification may not fully capture subtle changes in trunk position and orientation when sidestepping and thus may underestimate the outcomes. Next, it is important to acknowledge that the results and interpretation of group-average data may not apply to single athletes. Considerable variability in the magnitudes of energy absorption (Fig. 1) and individual responses to constraints were observed but were not the focus of this study. Lastly, joint kinematics were not considered due to our targeted focus on joint kinetics. While trunk and limb kinematics were not analysed as primary outcomes, visible changes in movement coordination under constraint conditions are likely to accompany shifts in mechanical demand. However, these associations are complex and not necessarily proportional, reinforcing the need to directly quantify joint kinetics when evaluating constraint-based training effects. The constraints used intended solely as a tool to acutely progress mechanical loading, not to teach or reinforce new execution strategies; any lasting neuromuscular adaptation would depend on training volume and programme structure far beyond the low-dose exposure used for mechanical overload.

In conclusion, the current study demonstrates that imposing task constraints during pre-planned sidesteps can significantly alter mechanical demands on the knee joint during early stance in female athletes. Specifically, holding a weighted implement at chest level (trunk constraint) increased energy absorption at the knee compared to unplanned, unconstrained sidesteps. Conversely, no significant changes were observed during unplanned conditions, likely due to a lower entry velocity. These findings support the use of task constraints to progressively expose athletes to higher knee loading, potentially enhancing tissue resilience and better preparing them for the mechanical demands encountered during competition and better prepare athletes for “worst-case” scenarios. This aligns with recent perspectives emphasising adaptability and robustness as key outcomes with representative and constraint-led training approaches<sup>54</sup>. Understanding how constraints alter lower-body joint loading can help design effective drills to overload single-joint capacities.

## Materials and methods

### Experimental approach to the problem

This blocked, partially counterbalanced crossover study examined the differences in knee joint kinetics across two tasks during pre-planned and unplanned sidestepping compared to unconstrained sidesteps. Six conditions were tested: pre-planned & unconstrained ( $PP_{free}$ ), unplanned & unconstrained ( $UP_{free}$ ), pre-planned & trunk constrained ( $PP_{trunk}$ ), unplanned & trunk constrained ( $UP_{trunk}$ ), pre-planned & preparatory step constrained ( $PP_{prep}$ ), unplanned & preparatory step constrained ( $UP_{prep}$ ). Outcome measures included entry velocity ( $m \cdot s^{-1}$ ) and sidestep angle ( $^{\circ}$ ) and continuous joint powers ( $W \cdot kg^{-1}$ ) for the ankle, knee and hip throughout the stance phase. Joint moments ( $Nm \cdot kg^{-1}$ ) were not part of the a priori hypotheses and were included only as exploratory analyses to help contextualise observed joint power patterns. Because the resultant joint power is a scalar measure that does not convey multiplanar loading composition, resultant and decomposed moments were

examined descriptively as supplementary mechanical information. These analyses are therefore not intended as inferential tests but are provided for mechanistic interpretation.

### Participants

Twenty-one trained female Australian Rules Football (ARF) players ( $n = 21$ ; age:  $23.5 \pm 4.5$  y, height:  $170.6 \pm 5.8$  cm, mass:  $67.5 \pm 6.6$  kg, ARF experience:  $5.8 \pm 4.5$  y, resistance training experience:  $3.5 \pm 2.5$  y) participated in this study. Participants were: (1) free of current lower limb injury and currently competing; (2) had not suffered an injury to the lower limb in the past 12 months requiring surgery; (3) free of any neuromuscular or musculoskeletal disorders that affected the lower limb and (4) had at least 12 months of ARF and resistance training experience. All participants were familiar with sidestepping maneuvers. This study was approved by the Edith Cowan University Human Research Ethics Committee (approval number: #22459). All methods were performed in accordance with relevant guidelines and regulations. Informed consent was obtained from all participants before inclusion in the study. A prior power analysis determined a minimum sample size of 20 participants using G\*Power (Version 3.1.9.6, University of Dusseldorf, Dusseldorf, Germany) based on a moderate effect size (Cohen's  $f$  of 0.5) between three different conditions (for the pre-planned and unplanned conditions, respectively), a power of 0.95, a type 1 error of 0.05, a correlation among repeated measures of 0.5 and a nonsphericity correction of 0.5. The effect size was based on the change in joint kinetics with constraints compared to unconstrained movements in vertical jumps, sprints and isometric mid-thigh pulls previously reported<sup>32–34</sup>.

### Sidestep protocol

Participants performed three to five pre-planned sidesteps and crossover steps, respectively, with only the right limb as warm-up. For clarity, participants would always sidestep to the left and crossover cut to the right. Although only the sidestepping trials to the left (off the right stance leg) were analysed, crossover cuts served as dummy trials to prevent pre-emption. A 10 m run-up was used to achieve a consistent approach velocity between  $3.5$  and  $4.5$  m·s<sup>-1</sup> and monitored with timing gates between 2 and 7 m before executing the sidestep on the force plate<sup>10,37,55</sup>. A 45° sidestep angle was indicated using adhesive tape lines marked on the force plate, but was not examined by trial, as the actual sidestep angle is often much lower upon execution<sup>10</sup>.

Data collection was blocked (planned then unplanned) and partially counterbalanced: PP<sub>free</sub> and UP<sub>free</sub> were completed first in their respective blocks, and the two constrained conditions were counterbalanced within each block (PP<sub>trunk</sub> vs PP<sub>prep</sub>; UP<sub>trunk</sub> vs UP<sub>prep</sub>). For all unplanned conditions, a 30 cm arrow displayed on a screen 3 m beyond the force plate indicated the cut direction after participants triggered timing gates 2 m before the force plate at a height of 0.8 m and width of 1.5 m<sup>37,56</sup>. This distance ensured participants had adequate time to react, but the tasks remained unplanned<sup>11</sup>. Participants were instructed to maintain a consistent approach velocity throughout each trial and focus on the screen to avoid force plate targeting with the execution leg.

For the trunk constraint, participants held an external load firmly against the chest with both hands and elbows flexed to ~90° throughout the task. Participants under 70 kg used a 4 kg load, and participants above 70 kg used a 6 kg load (~5–7.5% of body mass). The selection of this load range was guided by practicality and feasibility considerations. During pilot testing, heavier weights ( $\geq 7.5\%$  of body mass) excessively restricted trunk motion and led to conservative movement strategies, detracting from realistic sidestepping patterns. As such, this current mass range was sufficient to not compromise participants' ability to maintain typical sidestepping movement characteristics. This extra mass was added to the body mass for all subsequent calculations. To simplify the calculations, we added the mass to the participant, as the majority of the mass is already distributed to the trunk. Further amendments to the biomechanical model (adding the external mass to the trunk segment) did not make a difference beyond the accuracy reported in the current model<sup>57</sup>. For the preparatory step constraint, participants were ducked under an adjustable rope positioned at the participant's eye level 50 cm before the force plate, which corresponded to the penultimate foot placement prior to the sidestepping task (Fig. 2). Approximately 60 s of rest between each trial was provided to minimise fatigue. Trials were repeated if approach velocity deviated, foot placement was incorrect, or the incorrect direction was performed. Testing concluded after three valid sidestepping trials per condition.

### Data collection

Three-dimensional motion data were synchronously collected at 250 Hz using an 8-camera Vicon MX-series system (Vicon Peak Ltd., Oxford, UK). Ground reaction forces were synchronously collected at 1000 Hz using five 600 × 900 mm force plates (Kistler, Type 9290AD, Sindelfingen, Germany). Thirty-eight retroreflective markers were affixed following the University of Western Australia lower-body and torso marker set and model (Version 5)<sup>11,58</sup>. Single markers were attached to the left and right calcanei, left and right head of the first and fifth metatarsals, left and right anterior and posterior superior iliac spines, sternal notch, xiphoid process, seventh cervical vertebrae and twelfth thoracic vertebrae. Marker clusters for the creation of segment technical coordinate systems were attached to the left and right thigh and shank. To define the ankle joint, single markers were attached to the medial and lateral malleoli, and to define knee width for the functional joint center method below, single markers were positioned on the left and right medial and lateral epicondyles in the static calibration trials (removed for dynamic trials). Functional knee and hip tasks were performed to identify knee and hip joint axes and centers<sup>58</sup>. Kinematics of the hip, knee, and ankle followed ISB standards<sup>59</sup>. Joint kinetics were normalised to total body mass, which included the externally added mass in the trunk-loading condition, and expressed in the anatomical coordinate system of the distal segment. A total of 378 trials were subsequently analysed (Twenty-one participants \* six conditions \* three trials).

Data were processed using Vicon Nexus (Version 2.10, Vicon Motion Systems, UK) and analysed with Visual 3D software (Version 2020, C-motion, Inc., Rockville, MD). Kinematic and kinetic data were low-pass-filtered at

a cut-off frequency of 15 Hz, using a fourth-order, zero-lag, Butterworth recursive filter, determined via residual analysis<sup>60</sup>. Instantaneous resultant net joint power was calculated from joint angular velocities multiplied by net joint moments ( $P = M \cdot \omega$ ) and summed for all planes. Continuous joint power for the ankle, knee and hip was calculated during the execution step from initial contact to toe-off and linearly registered to 101 data points and used for the subsequent analysis. Initial contact and toe-off were identified using the vertical ground reaction force with a 20 N threshold. The knee resultant joint moment was computed as the square root of the sum of squared moments across the sagittal, frontal, and transverse planes, providing a single vector magnitude representing the net three-dimensional moment acting about the joint. Sidestep angle was calculated using the x- and y-coordinates of the stance foot ankle joint center at initial contact (x1 and y1) and the coordinates of the contralateral ankle joint center at initial contact (x2 and y2) using Eq. (1). The entry velocity was defined as the horizontal velocity of the COM at initial contact of the execution step (V@IC).

$$\text{Sidestep angle} = \tan^{-1} \left( \frac{a}{b} \right); \text{ where } a = |x2 - x1| \text{ and } b = |y2 - y1| \quad (1)$$

### Statistical analysis

Mean and standard deviation (SD) were calculated for all the entry velocities and sidestepping angles. Assumptions of homoscedasticity and normality were checked via residual plots and confirmed with Shapiro-Wilk and Levene's tests. Linear mixed-effects models analysed between-condition differences in all dependent variables using the residual maximum likelihood to estimate variance components. This approach enables the use of individual trials as distinct data points while accounting for within-participant effects and the correlated nature inherent in clustered data. Each condition was treated as fixed effect, with participant intercepts and by-participant random slopes for condition effects incorporated as random effects. When the fixed effect of condition was significant, pair-wise contrasts were Bonferroni-adjusted for the 15 possible comparisons among the six conditions ( $\alpha/15 = 0.0033$ ).

Cohen's effect sizes were calculated and interpreted as trivial (<0.2), small (0.2–0.49), moderate (0.5–0.79), and large (>0.8)<sup>61</sup>. Significance for the entry velocities and sidestepping angles were calculated using the gamlj package (Version 2.5.5), which applies Satterthwaite's method to estimate degrees of freedom and generate p-values in R Studio (Version 1.4.11.06, R Core Team 2018, <http://www.R-project.org/>).

Statistical parametric mapping (SPM) was used to compare stance phase joint power differences for the ankle, knee and hip separately between constrained and unconstrained conditions<sup>62</sup>. Only results for the first 30% of stance were interpreted as per our primary research questions, as this reflects the time periods of peak ACL loading and ACL injury occurrence<sup>63</sup>. A SPM one-way repeated measures analysis of variance (ANOVA) determined between-condition differences across all pre-planned and unplanned conditions with corrected  $\alpha$  to account for three joints and two conditions (with  $\alpha/6 = 0.0083$ ). Although the current method of ANOVA post-hoc analysis using the paired SPM T-test and Bonferroni correction is likely too simple, where an interaction effect was observed, post-hoc analysis was completed to further explore the capability of SPM analysis method for future hypothesis generation. Due to the current SPM post-hoc limitations, we compared the effects of these constraints separately within pre-planned and unplanned sidesteps to facilitate interpretation. As such, for post-hoc analyses, the alpha value was set at  $0.0083/3 = 0.0028$  for the number of post-hoc tests (between-condition comparisons) with 2-tailed inference analysis. The scalar output statistics (SPM{F} and SPM{T}) were calculated separately at each individual data point. Where the scalar output statistic crossed the critical threshold ({F} and {T}), the null hypothesis was rejected. Because of the smoothness of force-time curves and the inter-dependence of neighbouring points, multiple adjacent points of the SPM{F} or SPM{T} curve often exceed the critical threshold and are referred to as "suprathreshold clusters".

To supplement the joint-power findings, we performed two additional, exploratory SPM analyses covering (i) the resultant knee-joint moment and (ii) the decomposed knee moments about the sagittal (X), frontal (Y) and transverse (Z) axes. For the resultant moment, a one-way repeated-measures SPM{F} ANOVA was run separately for the pre-planned and unplanned tasks (Bonferroni-adjusted omnibus  $\alpha = 0.025$ ; post-hoc  $\alpha = 0.0083$ ). For the decomposed moments, six ANOVAs were needed (3 axes  $\times$  2 tasks), giving an omnibus  $\alpha = 0.0083$  and a post-hoc  $\alpha = 0.0028$ . Any supra-threshold clusters are reported as exploratory observations.

All SPM analyses were completed in the Spyder IDE (Version 5.5.4) distribution of Python (Version 3.10.11) using the open-source package "spm1d" (<http://www.spm1d.org/>). Statistical significance was set at  $\alpha \leq 0.05$ .

### Data availability

The dataset used (filtered and time-normalised relative joint power and relative knee joint moments, including the SPM code) can be provided from the corresponding author upon request.

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## Author contributions

DK and SN designed the study, recruited and managed data collection and conducted the analysis. All authors (DK, MJJ, JA, SN) contributed to the manuscript and interpretation of the results. All authors read and approved the final manuscript.

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## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

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