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Comparison of Knee Kinematics Between Sport and Lab Environments

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Abstract

The purpose of the study was to quantify knee joint kinematics and center of mass (CoM) speed between lab-based movements and sport-specific tasks in an ecologically relevant sport environment from varsity-level athletes. A total of seven lacrosse athletes completed tasks on in-fill turf, six lacrosse athletes on astroturf, eleven soccer athletes on in-fill turf, nine volleyball athletes on hard court, and five basketball athletes on hard court. Data collection took place in the sport environments and in a laboratory setting. Motion data were processed using a marker-less motion capture system. There was increased knee range of motion (RoM) during the sport-specific protocols compared to the laboratory tasks. Lacrosse athletes exhibited greater knee RoM while performing cutting maneuvers in a sport specific environment than in a laboratory. There was no significant difference in knee RoM for soccer athletes. In basketball athletes, there was a significant kinematic difference during the on-court lane agility drill than the sidestep cuts in the laboratory. Movements in clinical settings may not capture the complexities of sport. The study highlights the importance of considering sport-specific demands in assessing athletes' return to sport. Future research should explore whether sport-environment assessment improves readiness decisions after rehabilitation.

Keywords: motion capture; sport environment; knee; kinematics

1. Introduction

Surgical reconstruction of the ACL (ACLR) is the most common treatment of ACL injuries with the goal of re-establishing pre-injury knee motion [1]. Following ACLR, patients are routinely assessed using various return-to sport (RTS) assessment tasks (e.g., horizontal and vertical jumping tasks). However, only 23% of patients pass RTS test batteries after ACLR, and passing does not significantly reduce the overall risk of a subsequent ACL injury [2]. Furthermore, an estimated 50–90% of ACL-injured patients develop post-traumatic osteoarthritis over long-term follow-up [3], and youth with sport-related knee injuries exhibit higher adiposity, weaker knee musculature, and poorer self-reported knee outcomes than uninjured peers 3–10 years post-injury [4]. A potential limitation of current RTS assessments is that they are often conducted in controlled clinical or laboratory settings that may not reflect the demands of sport.

Extrinsic factors, such as the performance environment, may have an influence on the assessment of an athlete's movement patterns [5]. While clinical or lab-based assessments may involve tasks such as sidestep cuts or stop jumps, they do not address the potential influence of equipment, sport specific objectives, or sport-specific playing surfaces. For

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example, harder surfaces may result in larger peak forces compared to similar movements on softer surfaces [6]. Additionally, field sport athletes experience alterations in vertical and horizontal braking forces, and hip and knee moments when performing bilateral drop jumps, unilateral drop jumps, and a 90° cutting manoeuvre on softer surfaces (e.g., artificial turf) compared to harder surfaces (e.g., Mondo track). Therefore, movement assessments that are completed in a clinic or a research laboratory are likely performed on surfaces that are not indicative of the actual playing surfaces and may affect the outcome of these important assessments. Kinematic patterns observed in lab settings may not represent those performed during sport. Recent advancements in marker-less motion capture enable data collection in sport environments without the spatial constraints commonly seen in lab settings [7]. While Kanko et al. [7] validated a marker-less system during walking, Song et al. [8] reported RMSD $\leq$ 5.9° for knee angles across eight movements (including sidestep cutting), and Kanko et al. [9] reported 5–10° RMSD for frontal and transverse plane angles during running. It is currently unclear if movement patterns are different between sport and laboratory environments and tasks. Sport environments offer greater spatial freedom than laboratories, where walls and equipment limit the distance available for acceleration and deceleration, potentially constraining movement velocity and amplitude. The interaction between sport-specific footwear (e.g., cleats, court shoes) and playing surfaces (e.g., turf, hardwood) may produce higher coefficients of friction than running shoes on laboratory flooring, which may facilitate higher approach speeds and more aggressive changes of direction. Also, sport-specific tasks involve greater movement complexity and sport objectives (e.g., carrying a lacrosse stick, dribbling a ball) that may alter neuromuscular demand and increase the kinematic excursions required to complete the task.

Therefore, the purpose of this research was to quantify and compare knee joint kinematics and center of mass speed between laboratory tasks and sport-specific tasks performed in a sporting environment. It was hypothesized that tasks performed in the sport-specific environments would have a greater knee range of motion (RoM) and greater center of mass (CoM) speed.

2. Materials and Methods

A total of 33 varsity-level athletes completed a series of movements in a lab and sport-specific environment (Table 1). Athletes were eligible to participate if they were: (i) between 18–40 years of age; (ii) healthy with no current lower extremity pathologies; (iii) were on the varsity lacrosse, soccer, volleyball, or basketball teams. Athletes were excluded if: (i) they had lower limb injuries/surgeries within the past 12 months affecting gait; (ii) had any surgery to the lower extremity and/or back; (iii) had any injury to the lower extremity and/or back in the last 6 months; (iv) had any current discomfort in the lower extremity and/or back; (v) were diagnosed with any neurological impairment or vestibular disorder that may affect balance; (vi) had been diagnosed with a concussion within the past year; or (vii) were taking medication that may affect balance. Participant eligibility was verbally confirmed prior to providing the athletes with the written informed consent. Research Electronic Data Capture (REDCap 16.0.55; Vanderbilt University, Nashville, TN, USA) forms were used to collect participant demographics.

It should be noted that eight lacrosse athletes (L #1–8) completed the same standardised lab protocol. However, not every athlete collected sport-environment data on both playing surfaces due to scheduling constraints. The participant availability was as follows: In-fill turf: seven complete pairs (L #1, 2, 3, 5, 6, 7, 8); L #4 excluded (no In-fill data); Astroturf: six complete pairs (L #1, 2, 3, 4, 5, 8); L #6 and #7 excluded (no Astroturf data). Lab-based tasks were selected because they represent commonly used controlled movement assessments, while sport-specific tasks were selected to reflect more ecologically relevant

movement tasks. Motion data were recorded in both the laboratory and sport environments using a marker-less motion capture system (Theia Markerless Inc. v2023.1.0.3161, Kingston, ON, Canada) consisting of eight synchronized cameras sampling at 120 Hz (Sony Cybershot DSC-RX0M2, Minato, Tokyo, Japan). Kinematics were quantified using three DoF (flexion/extension, abduction/adduction, and internal/external rotation) at the hip, knee, and ankle joints, and a 20 Hz-equivalent GCVSPL cut-off frequency for each kinematic evaluation was applied [10]. A cut-off frequency of 20 Hz is recommended for higher-rate activities such as running [11]. In both the sport and laboratory environments, a 5-second static trial of the capture volume was collected using object calibration. Therefore, all subsequent trials were standardized to the calibration file. The positioning of the cameras was such that they surrounded the data collection site and had an unobstructed view of the participant. Knee joint kinematic data were calculated and extracted in Visual 3D (C-Motion, Kingston, ON, Canada) using an XYZ cardan sequence, capturing the relative orientation of the shank to the femur. The *X*-axis was defined as the mediolateral axis of the femur, corresponding to flexion/extension; the *Y*-axis was defined as the longitudinal axis of the shank, corresponding to internal/external rotation; and the *Z*-axis was the floating axis mutually perpendicular to X and Y, corresponding to abduction/adduction [12]. Extension, adduction, and internal rotation were positive for the right leg and extension, while abduction and external rotation were positive for the left leg. Center of mass speed was also calculated and extracted in Visual 3D. Visual3D's default whole-body centre-of-mass model was used. This is a 15-segment anthropometric model (head, trunk, pelvis, upper arms, forearms, hands, thighs, shanks, feet). CoM position is the mass-weighted average of individual segment centres of gravity. CoM speed is the resultant of the first-derivative velocity vector ($\sqrt{(Vx^2 + Vy^2 + Vz^2)}$) extracted at the IC frame.

Table 1. The breakdown of the athletes that participated in the study across the different sports.

	Lacrosse: In-Fill Turf (n = 7)	**Lacrosse: Astroturf (n = 6)**	**Soccer (n = 11)**	**Volleyball (n = 9)**	**Basketball (n = 5)**
Males	5	3	6	6	2
Females	2	3	5	3	3
Mean [SD] Age (years)	21.4 [3.67]	21.0 [4.16]	19.6 [0.77]	20.0 [0.94]	20.60 [1.67]
Mean [SD] Height (cm)	173.4 [11.4]	171.2 [12.3]	174.1 [7.37]	185.3 [8.75]	179.10 [10.61]
Mean [SD] Weight (kg)	76.4 [16.2]	74.3 [17.9]	73.1 [8.98]	80.6 [8.71]	80.60 [6.54]
Mean [SD] BMI	25.2 [3.97]	25.1 [4.32]	24.0 [1.76]	23.4 [1.53]	25.18 [1.86]

Basketball athletes completed a lane agility drill (Figure 1a) [13] that required them to start in a stationary running stance facing the baseline on the left side of the free-throw line where a cone was placed for reference. When told to go, the participant ran towards the baseline, shuffled to the right across the baseline, ran backwards up the key, shuffled across the free-throw line to the cone, shuffled back across the free-throw line, ran down the key to the baseline, shuffled to the left across the baseline, and ran backwards to the cone to finish (Figure 1a). Basketball athletes completed these tasks on University of Toronto's regulation-sized basketball court composed of hardwood wearing their own basketball shoes.

Lacrosse athletes completed a lacrosse-specific three-cone drill (Figure 1b) [14]. Three cones were placed approximately 5 m apart in an "L" formation where one cone was in

front of the first cone and the last cone was to the right of the second cone (Figure 1b). The participant, while holding a lacrosse stick with a ball in the mesh, ran as quickly as possible toward the second cone, then ran back to the first cone, around the outside of the second cone, around the third cone from the inside, around the outside of the second cone, and back to the first cone. Lacrosse athletes completed these tasks on the University of Toronto's regulation-sized football field, which is composed of in-fill turf, and also on the University of Toronto's regulation-sized field hockey field, which is composed of a commercial-grade AstroTurf, wearing their own cleats and running shoes, respectively.

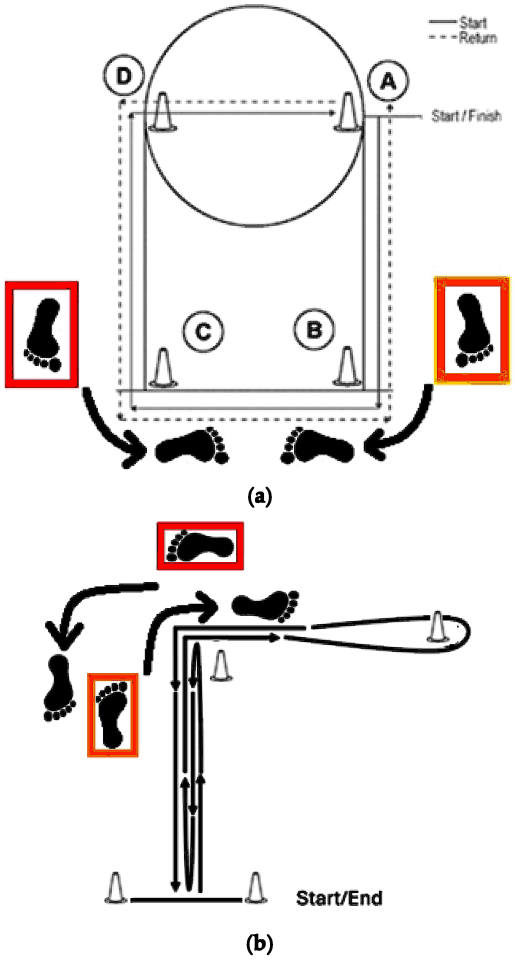


Figure 1. Image of the cutting tasks performing a (**a**) basketball-specific lane-agility drill and (**b**) lacrosse-specific and soccer-specific three-cone drill highlights, which steps were extracted and analyzed from the athletes. The analyzed step with the right foot is highlighted in red, and the left is highlighted in orange.

Soccer athletes completed a soccer-specific three-cone drill (Figure 1b). Three cones were placed approximately 5 m apart in an "L" formation where one cone was in front of the first cone and the last cone was to the right of the second cone (Figure 1b). The participant, while dribbling the ball on their feet, ran as quickly as possible toward the second cone, then ran back to the first cone, around the outside of the second cone, around the third cone from the inside, around the outside of the second cone, and back to the first cone. Soccer athletes completed these tasks on the University of Toronto's regulation-sized football field, which is composed of in-fill turf, wearing their own cleats. A photo of a soccer athlete in a lab environment and on in-fill turf is shown in Figure 2.

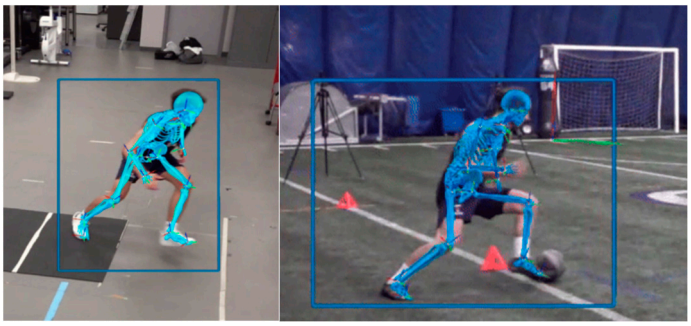


Figure 2. Image of a soccer athlete performing a cutting task in a lab environment (**left**) and a soccer specific three-cone drill on in-fill turf (**right**).

Volleyball athletes completed an approaching jump off with two feet [15]. The participants were instructed to step forward with one foot and then step with the other (they were given the choice of which foot to step with first) and to jump as high as possible. The volleyball athletes completed the task on University of Toronto's regulation-sized volleyball court composed of hardwood wearing their own volleyball shoes.

In the laboratory, basketball, lacrosse, and soccer athletes performed a sidestep cut. For this task, participants were instructed to run towards a pre-determined area 5 m away, decelerate, and touch the area with the contralateral leg during a 90° cutting manoeuvre. Volleyball athletes also visited the laboratory and performed a stop jump. For the stop jump, participants ran 5 m, decelerated, performed a two-footed jump, and immediately performed a maximal countermovement vertical jump.

The same 8-camera set (Sony DSC-RX0M2) was deployed at every location (laboratory, astroturf, in-fill turf, basketball court, volleyball court). At each environment, a 5 s static object-based calibration trial of the capture volume was collected prior to data collection. All subsequent trials within that session were standardised to the session calibration file. Camera placement surrounded the data-collection site to ensure an unobstructed multi-view observation of the participant. The lab-based and sport-specific tasks were intentionally selected to represent different levels of ecological relevance rather than identical movements performed in two environments. The lab tasks (sidestep cut, stop jump) reflect standardized assessments commonly used in clinical injury risk screening and return-to-sport evaluation, while the sport-specific tasks (three-cone drill, lane agility drill, approaching jump) represent movement patterns encountered during competition. This design was chosen to evaluate whether commonly used clinical assessments capture the kinematic demands that athletes experience during sport-specific activities, which is the clinically relevant comparison for practitioners making return-to-sport decisions. The laboratory session was completed first for all participants, followed by the sport-environment session on a separate day. Within each session, tasks were performed in a randomized order. Athletes performed as many practice trials as they wanted of each task before feeling comfortable for recorded trials. A rest period was provided between trials if the athlete needed it. All three recorded trials per task were retained for analysis.

For both the laboratory and sport-specific cutting tasks, the three-dimensional knee joint kinematics were time normalised between the time of initial contact of the cutting foot and at 200 ms after initial contact. Although the sport-specific tasks were more complex in their overall structure (e.g., multi-directional drills with sport equipment), the specific movement epoch analysed in each case was a comparable cutting or landing action. For the cutting sports (lacrosse, soccer, basketball), the analysed step within the sport-specific drill was a directional change that functionally matched the laboratory sidestep cut. Similarly, for volleyball, the landing phase of the on-court approaching jump was compared to the

landing phase of the laboratory stop jump. In this way, the kinematic comparison between environments was based on a biomechanically analogous movement phase extracted from each task, even though the broader task context differed. Along with a visual inspection, for cutting tasks (lacrosse, soccer, basketball), initial contact was identified as the vertical position minimum of the heel, corresponding to the specific cutting step within the trial. The vertical position minima of the foot did not occur during foot contact before or after the marked area. Initial contact also occurred in the landing phase of the jumping task.

For jumping tasks (volleyball), initial contact was identified through a multi-step pipeline applied to the distal toe landmark in Visual 3D. The global vertical maximum (jump apex) and minimum (ground level) were first detected, and initial contact was defined as the landing event between the descent phase and the vertical minimum using the Event_Between command until it reached zero. A single frame was obtained from the pipeline, providing a deterministic, single-frame initial contact event. The 1-frame sensitivity analysis examined all variables (IC angles, 200 ms angles, RoM) across all jumping trials and was insensitive in the analysis. The analysed landing was the countermovement jump landing (after the jump apex), corresponding to the landing phase of the on-court approaching jump. All automatically detected events were visually verified against the plotted vertical trajectory of the heel or toe landmark. Toe-off was checked from foot-marker kinematics. The 200 ms endpoint was defined as initial contact + 200 ms (24 frame intervals at 120 Hz), and joint RoM (sign invariant) was computed as the range (max − min) of each angle component within this window. For the jumping task, the kinematic signals were time-normalised between initial foot contact and 200 ms after initial contact. For both the cutting and jumping tasks, the total joint range of motion (about all three axes separately) was quantified within the initial contact to 200 ms post-contact cycle. The 200 ms window captures the weight acceptance phase after ground contact (the period of greatest ACL injury risk). This functional phase is present in both cutting (deceleration to direction change on the plant foot) and landing (impact absorption after flight) tasks. The window was chosen to be consistent with prior ACL biomechanics literature [16], as well as to standardize the analysis interval across tasks with different stance durations. For cutting tasks, the plant foot remained grounded throughout the direction change. Therefore, weight acceptance and redirection occur well within the 200 ms window. For the jump landing, the athlete absorbed impact with both feet planted and no toe-off occured within 200 ms of landing. The RoM files consistently contain the expected 24 frames, confirming no data truncation due to early toe-off. For the dataset used, single frame shifts were insensitive (median 0.00°). Systematic IC bias is unlikely because the same algorithm and pipeline were applied to both lab and sport trials. Any frame-level jitter would affect both conditions equally and would not inflate between-environment differences.

The RoM calculations were performed in MATLAB R2021b (Mathworks Inc., Natick, MA, USA), and the mean of the three trials for each task was quantified and used in subsequent statistical analysis. The time-normalized plots were created in MATLAB. Calculations for athlete CoM speed at initial contact during the cutting task was also quantified in MATLAB, and the mean of the three trials for each task was used in subsequent statistical analysis. To determine if there were statistically significant differences between environments, separate repeated-measures ANOVA were performed on each of the knee joint kinematic variables for each group of athletes. Task condition (laboratory vs. sport-specific) and limb (left vs. right) were included as within-subject factors. Data were assessed for and met the conditions for normality for all variables using the Shapiro-Wilk test. All signed angles (IC, 200 ms) retained their native sign conventions from Visual3D. Limbs were not combined for bilateral analysis of signed angles. Within each table (sport × surface), the Holm-Bonferroni correction was applied to control the family-wise error rate at $\alpha = 0.05$.

Effect sizes are Cohen's d for paired samples (d = mean difference/SD of differences). The 95% confidence intervals around the mean difference are unadjusted with n − 1 degrees of freedom. All statistical tests were performed in SPSS version 29 (IBM SPSS Statistics, Armonk, NY, USA).

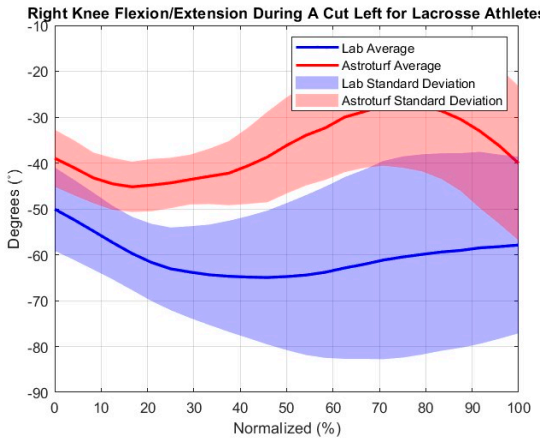
3. Results

When adjusting for the *p*-value (Table A1) in lacrosse athletes, right knee RoM for knee abduction/adduction (F (1,5) = 41.63, $p = 0.027$) (Table 2) was significantly greater during the cutting phase of the task performed on the astroturf than the sidestep cut in a laboratory environment (Figure 3).

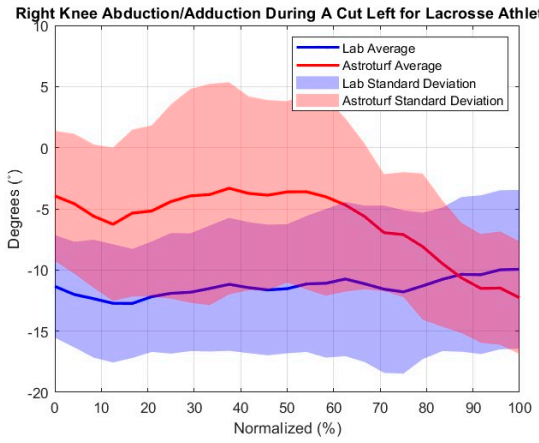
Table 2. Comparison of mean (SD) RoM and joint angle values in the right and left knee during a three-cone drill on the astroturf to the left and a cut left in lab from lacrosse athletes, and a three-cone drill on the astroturf to the right and cut right in lab from lacrosse athletes.

	Right Knee (Cut Left)		Left Knee (Cut Right)	
	In-Lab	**Astroturf Three Cone Drill**	**In-Lab**	**Astroturf Three Cone Drill**
RoM Flexion/Extension (°)	30.71 [6.87]	37.58 [9.42]	32.63 [9.54]	35.34 [7.36]
RoM Abduction/Adduction (°)	10.43 [2.69]	20.76 [2.63] *	9.25 [3.25]	20.83 [10.84]
RoM Internal/External Rotation (°)	18.99 [1.95]	29.91 [5.30]	15.63 [2.39]	31.37 [10.01]
IC Flexion/Extension (°)	−51.65 [10.16]	−39.58 [6.87]	−46.46 [10.23]	−37.68 [8.66]
IC Abduction/Adduction (°)	−10.96 [4.78]	−2.74 [6.33]	6.23 [4.47]	−0.73 [7.55]
IC Internal/External Rotation (°)	−6.97 [9.19]	−12.56 [5.56]	11.27 [4.00]	16.45 [11.83]
200 ms after IC Flexion/Extension (°)	−53.83 [20.85]	−40.99 [16.16]	−59.53 [6.03]	−54.42 [11.04]
200 ms after IC Abduction/Adduction (°)	−8.96 [7.31]	−11.65 [5.45]	7.23 [6.10]	−3.20 [8.64]
200 ms after IC Internal/External Rotation (°)	−4.69 [12.11]	−18.75 [4.72]	7.57 [8.52]	12.63 [6.48]

* = denotes significance. IC = initial contact.

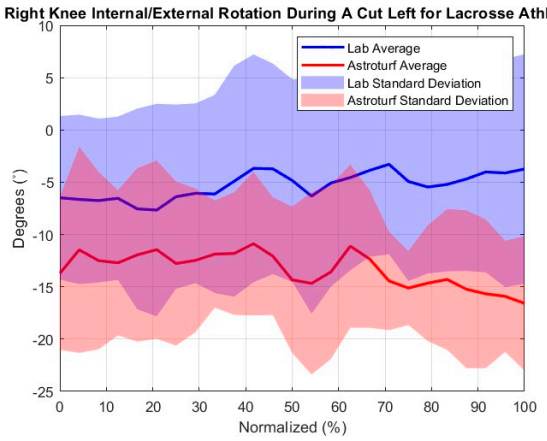


(a)

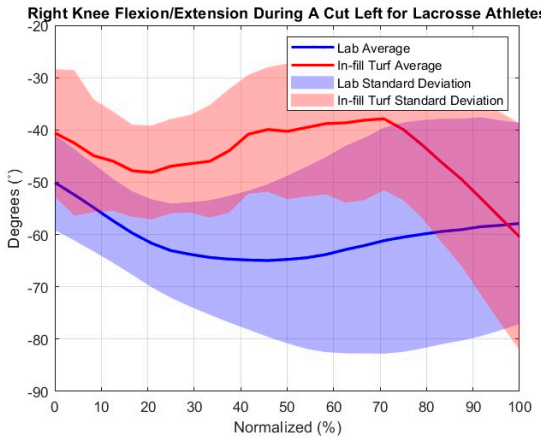


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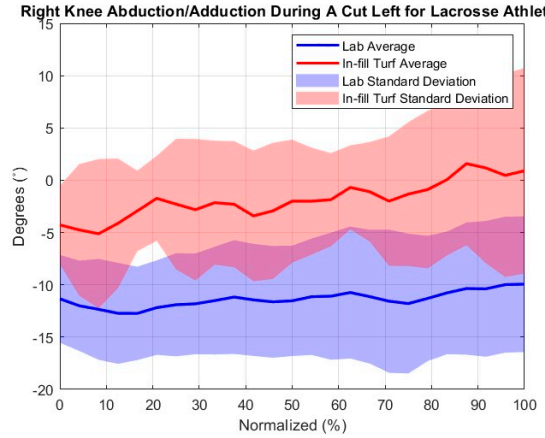
Figure 3. *Cont.*



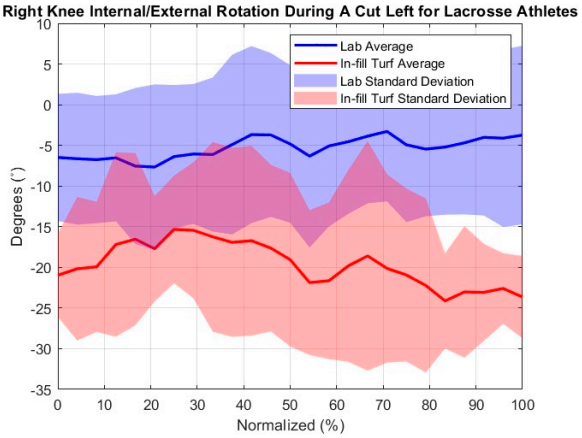
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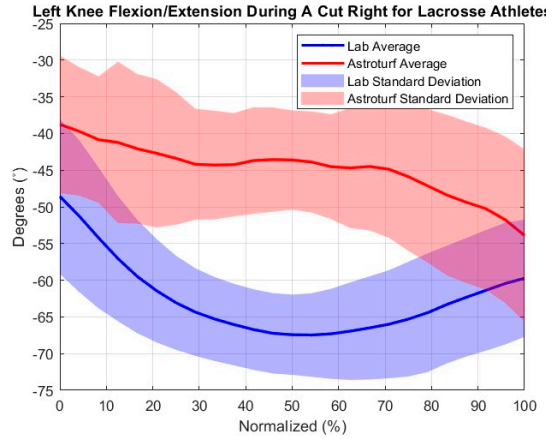
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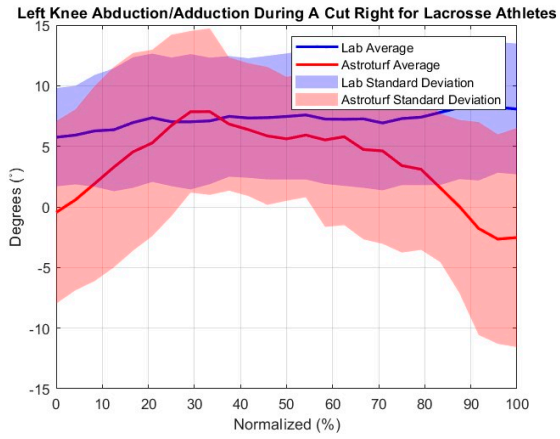
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Figure 3. *Cont.*

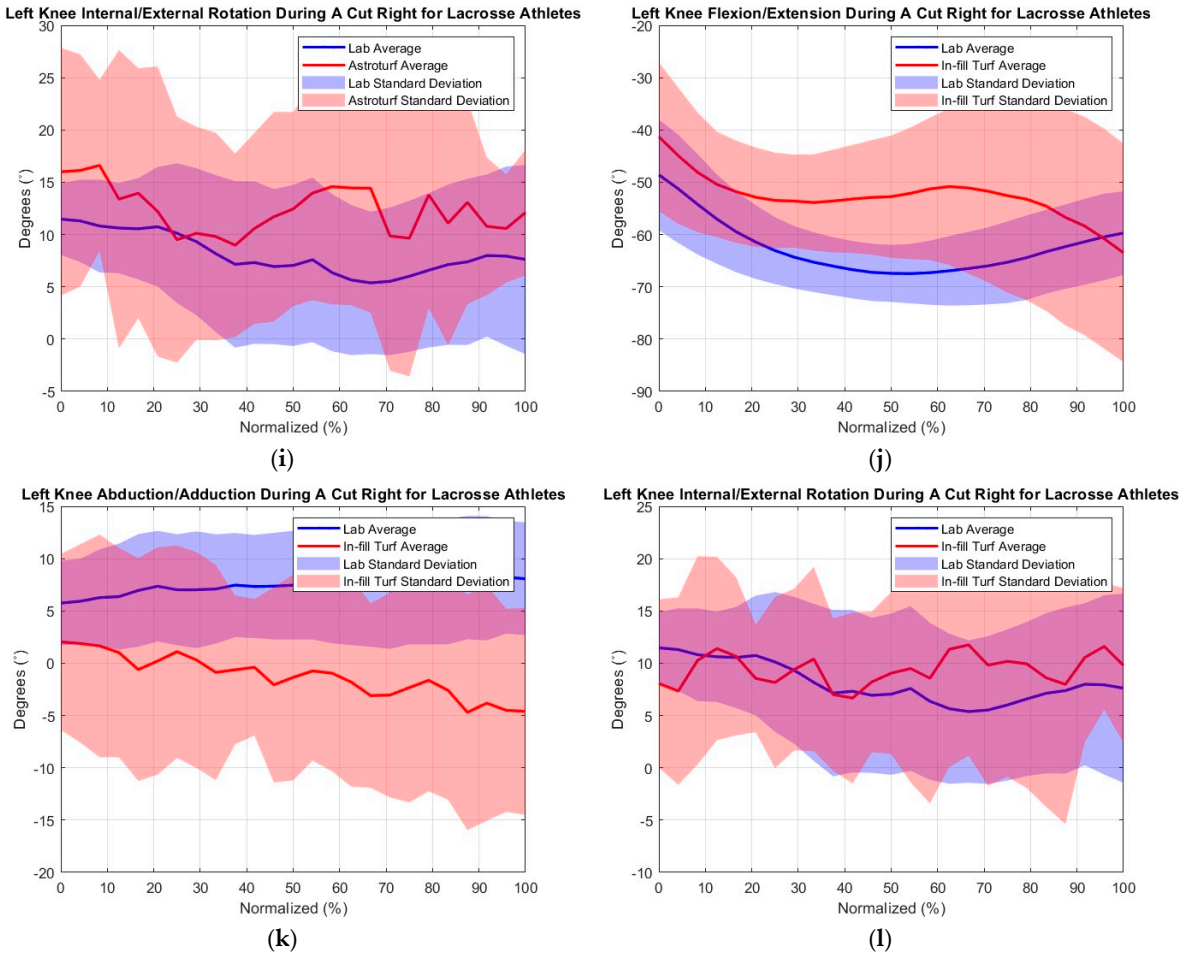


Figure 3. Time-series plots of lacrosse athletes' right knee during a cut left on astroturf (**a**–**c**), right knee during a cut left on in-fill turf (**d**–**f**), left knee during a cut right on astroturf (**g**–**i**), and left knee during a cut right on in-fill turf (**j**–**l**) showing greater knee RoM than the laboratory environment. Time-series axes are normalized to percentages of the fixed 200 ms window.

Similar results were obtained for lacrosse athletes on the in-fill turf. After adjusting for the *p*-value (Table A2), right knee external rotation (F (1,6) = 25.82, $p = 0.038$) (Table 3) at initial contact was significantly greater on the in-fill turf than in the laboratory environment.

After adjusting the *p*-value (Table A2), knee RoM abduction/adduction (Right Knee: F (1,6) = 38.57, $p = 0.014$; Left Knee: F (1,6) = 92.67, $p = 0.001$) and left knee internal/external rotation (F (1,6) = 48.69, $p = 0.008$) (Table 3) were significantly greater on the in-fill turf than in the laboratory environment. It is also reflected in the excursion of the averaged curve (Figure 3).

After adjusting for the *p*-value (Table A3), there were no significant differences between knee RoM and CoM speed in soccer athletes (Table 4). However, the absence of statistical significance does not establish equivalence between protocols, particularly given the sample size (n = 11) and the measurement precision of the frontal and transverse planes.

In basketball athletes, after adjusting for *p*-value (Table A4), there were no significant differences at initial contact or 200 ms after contact (Table 5).

However, for basketball athletes, left knee RoM for internal/external rotation (F (1,4) = 59.33, $p = 0.031$) (Table 5) was significantly greater on the court than the laboratory environment (Figure 4).

In volleyball athletes, after adjusting for the *p*-value (Table A5), there were no significant differences at initial contact and 200 ms after contact (Table 6).

Table 3. Comparison of mean (SD) RoM and joint angle values in the right and left knee during a three-cone drill on the in-fill turf to the left and a cut left in lab from lacrosse athletes, and a three-cone drill on the in-fill turf to the right and cut right in lab from lacrosse athletes.

	Right Knee (Cut Left)		Left Knee (Cut Right)	
	In-Lab	**In-Fill Three Cone Drill**	**In-Lab**	**In-Fill Three Cone Drill**
RoM Flexion/Extension (°)	32.02 [7.89]	41.80 [17.71]	31.94 [9.15]	33.23 [5.63]
RoM Abduction/Adduction (°)	10.23 [2.47]	19.86 [4.20] *	9.72 [3.10]	21.26 [3.91] *
RoM Internal/External Rotation (°)	18.18 [1.93]	32.02 [13.34]	15.91 [2.40]	30.64 [6.32] *
IC Flexion/Extension (°)	−50.55 [9.72]	−40.58 [12.18]	−48.12 [11.32]	−41.31 [14.25]
IC Abduction/Adduction (°)	−10.90 [4.33]	−4.28 [3.77]	4.63 [2.72]	2.04 [8.43]
IC Internal/External Rotation (°)	−6.05 [8.34]	−20.96 [5.12] *	11.45 [3.69]	8.06 [8.05]
200 ms after IC Flexion/Extension (°)	−62.21 [16.05]	−60.44 [21.67]	−59.11 [8.43]	−63.50 [20.88]
200 ms after IC Abduction/Adduction (°)	−10.56 [6.75]	0.90 [9.83]	6.86 [4.48]	−4.61 [9.89]
200 ms after IC Internal/ External Rotation (°)	−2.28 [10.99]	−23.65 [5.06]	6.75 [9.41]	9.79 [7.41]

* = denotes significance. IC = initial contact.

Table 4. Comparison of mean [SD] RoM and joint angle values in the right and left knee during a three-cone drill on the in-fill turf to the left and a cut left in lab from soccer athletes, and a three-cone drill on the in-fill turf to the right and cut right in lab from soccer athletes.

	Right Knee (Cut Left)		Left Knee (Cut Right)	
	In-Lab	**In-Fill Three Cone Drill**	**In-Lab**	**In-Fill Three Cone Drill**
RoM Flexion/Extension (°)	35.13 [10.69]	34.40 [6.54]	32.80 [11.42]	31.90 [7.02]
RoM Abduction/Adduction (°)	7.53 [3.38]	8.78 [2.42]	9.19 [3.81]	7.11 [2.93]
RoM Internal/External Rotation (°)	15.44 [5.18]	17.31 [5.55]	16.60 [4.89]	16.21 [5.99]
IC Flexion/Extension (°)	−37.69 [13.52]	−41.95 [7.18]	−39.47 [13.67]	−44.73 [17.16]
IC Abduction/Adduction (°)	−5.54 [4.10]	−1.73 [3.11]	5.78 [7.36]	4.00 [2.86]
IC Internal/External Rotation (°)	−10.89 [4.44]	−11.85 [4.91]	12.04 [4.84]	7.33 [7.81]
200 ms after IC Flexion/Extension (°)	−58.59 [16.21]	−47.82 [14.51]	−58.37 [14.09]	−44.48 [11.12]
200 ms after IC Abduction/Adduction (°)	−6.26 [5.79]	0.43 [2.89]	4.88 [6.53]	1.56 [4.69]
200 ms after IC Internal/ External Rotation (°)	−6.24 [6.51]	−16.64 [6.61]	7.09 [8.16]	14.48 [7.21]

Table 5. Comparison of mean (SD) RoM and joint angle values in the right and left knee during a lane agility drill on court to the left and a cut left in lab from basketball athletes, and a lane agility drill on court to the right and cut right in lab from basketball athletes.

	Right Knee (Cut Left)		Left Knee (Cut Right)	
	In-Lab	**On-Court Lane Agility Drill**	**In-Lab**	**On-Court Lane Agility Drill**
RoM Flexion/Extension (°)	34.45 [10.25]	41.21 [7.50]	28.70 [7.13]	33.26 [6.92]
RoM Abduction/Adduction (°)	8.98 [1.80]	31.57 [8.05]	7.90 [4.01]	22.22 [8.25]
RoM Internal/External Rotation (°)	16.43 [4.20]	41.89 [14.77]	10.01 [1.82]	32.81 [5.39] *
IC Flexion/Extension (°)	−46.82 [8.94]	−46.59 [6.44]	−42.52 [4.02]	−54.55 [9.22]
IC Abduction/Adduction (°)	−8.36 [8.53]	−13.85 [6.14]	7.72 [3.57]	7.79 [9.38]

Table 5. *Cont.*

	Right Knee (Cut Left)		Left Knee (Cut Right)	
	In-Lab	**On-Court Lane Agility Drill**	**In-Lab**	**On-Court Lane Agility Drill**
IC Internal/External Rotation (°)	−4.65 [3.10]	−4.70 [11.00]	4.89 [6.54]	11.02 [8.51]
200 ms after IC Flexion/Extension (°)	−43.29 [21.21]	−49.30 [10.18]	−49.16 [11.84]	−59.67 [7.07]
200 ms after IC Abduction/Adduction (°)	−2.67 [9.79]	−18.02 [4.33]	5.63 [3.98]	10.56 [6.14]
200 ms after IC Internal/ External Rotation (°)	−4.22 [12.68]	−7.81 [13.82]	2.64 [5.60]	2.75 [8.89]

* = denotes significance. IC = initial contact.

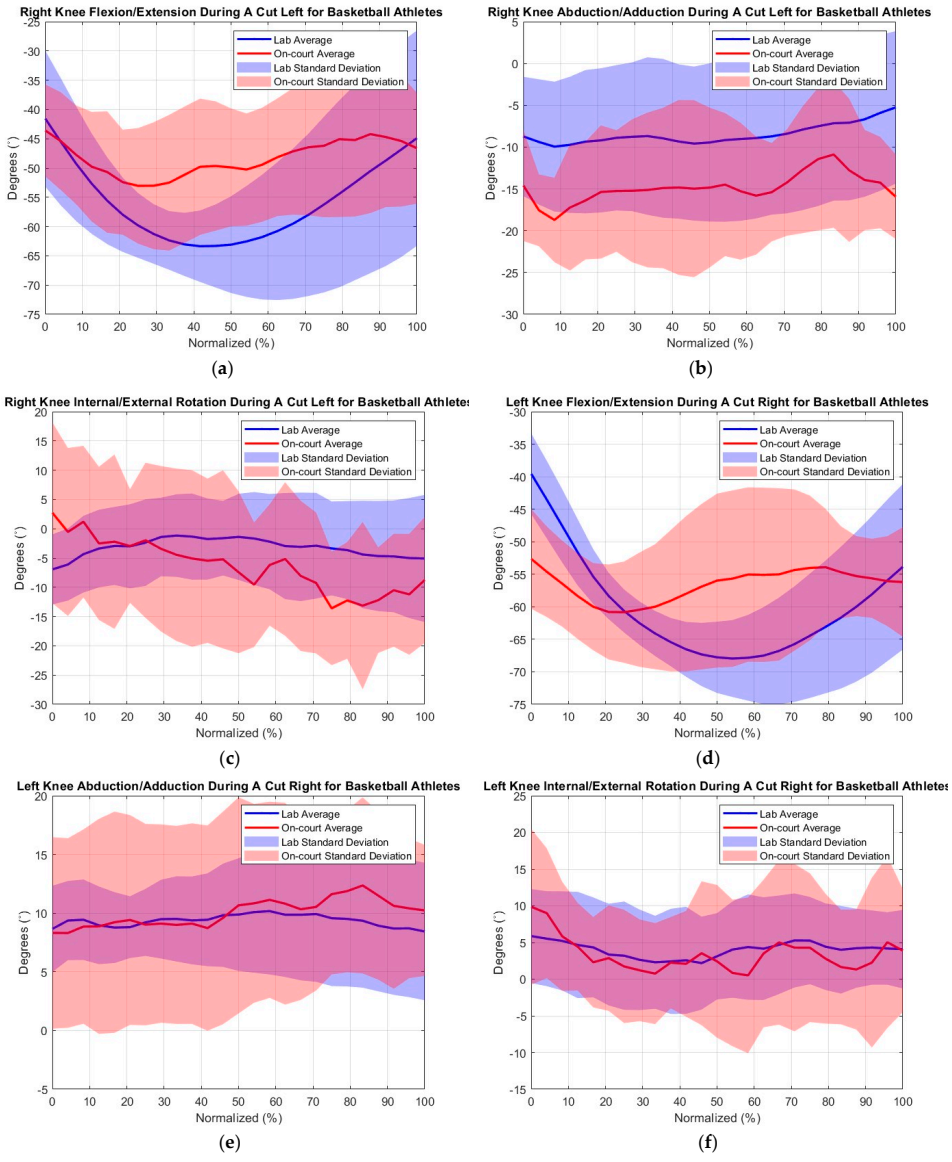


Figure 4. Time-series plots of basketball athletes of the right knee during a cut left on court (**a**–**c**), and left knee during a cut right on on court (**d**–**f**) shows greater knee RoM than the laboratory environment. Time-series axes are normalized to percentages of the fixed 200 ms window.

After adjusting the *p*-value, there were also no significant differences for RoM for volleyball athletes (Figure 5).

Table 6. Comparison of mean (SD) RoM and joint angle values in the right and left knee during an approaching jump on court and a stop jump in lab from volleyball athletes.

	Right Knee		Left Knee	
	In-Lab Stop Jump	**On-Court Approaching Jump**	**In-Lab Stop Jump**	**On-Court Approaching Jump**
RoM Flexion/Extension (°)	69.57 [8.69]	68.66 [13.27]	69.79 [9.81]	61.68 [18.45]
RoM Abduction/Adduction (°)	7.53 [2.25]	8.16 [4.91]	6.89 [2.68]	8.94 [4.32]
RoM Internal/External Rotation (°)	11.19 [2.56]	13.20 [3.87]	9.26 [3.22]	15.31 [5.40]
IC Flexion/Extension (°)	−32.14 [9.06]	−25.65 [10.59]	−29.94 [7.78]	−32.24 [14.08]
IC Abduction/Adduction (°)	0.38 [2.50]	0.05 [3.60]	−1.51 [2.87]	0.13 [2.19]
IC Internal/External Rotation (°)	−7.58 [6.54]	−11.84 [6.43]	5.80 [4.15]	5.36 [4.60]
200 ms after IC Flexion/Extension (°)	−99.60 [10.40]	−88.86 [12.35]	−99.71 [11.09]	−86.97 [14.57]
200 ms after IC Abduction/Adduction (°)	−4.54 [3.34]	−4.06 [6.29]	2.87 [2.29]	4.13 [5.82]
200 ms after IC Internal/ External Rotation (°)	−1.91 [6.39]	−6.10 [7.19]	0.29 [6.59]	3.08 [7.12]

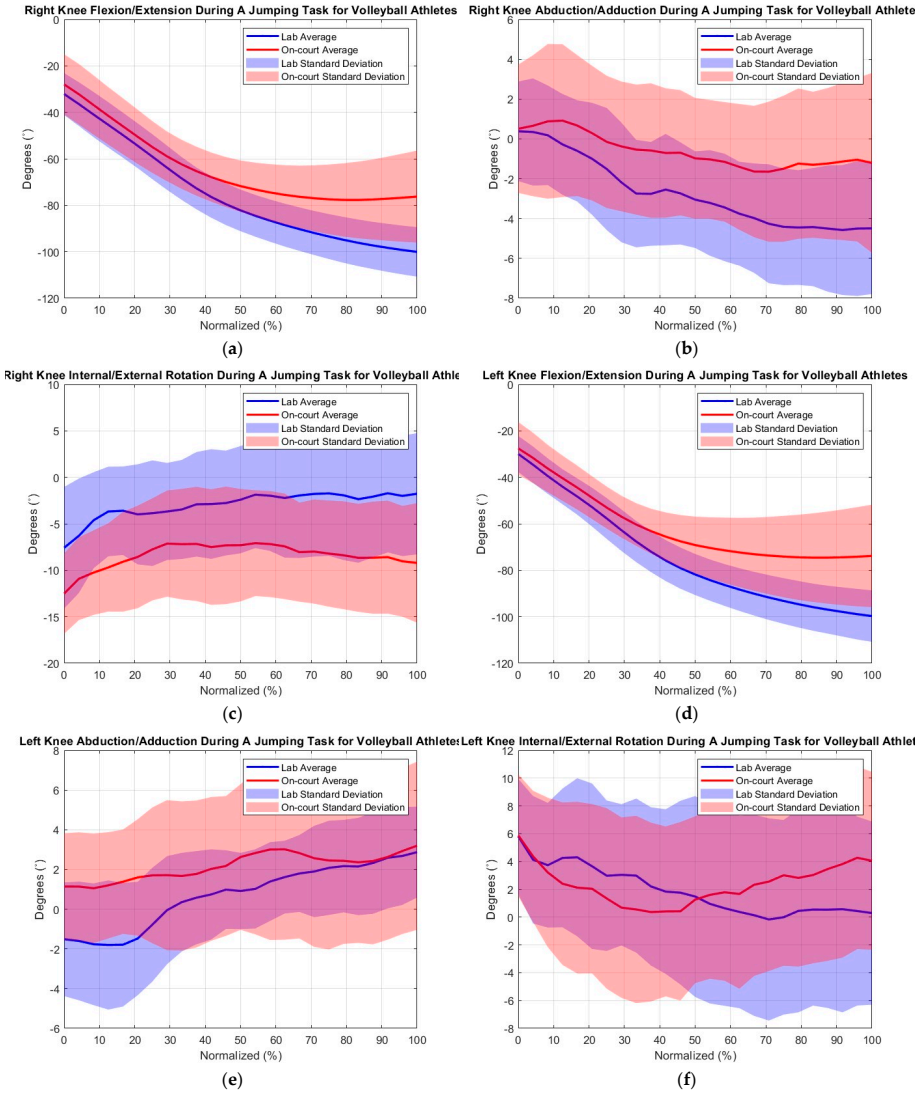


Figure 5. A comparison of time-series plots of volleyball athletes' right knee during a jumping task on court (**a**–**c**), and left knee during a jumping task on court (**d**–**f**). Time-series axes are normalized to percentages of the fixed 200 ms window.

After adjusting for the *p*-value, there were also no significant differences in CoM speed for the lacrosse, soccer, and basketball athletes (Figure 6). When looking at all sports, planes, and outcomes, there were six significant differences when adjusting the *p*-value (Table A6).

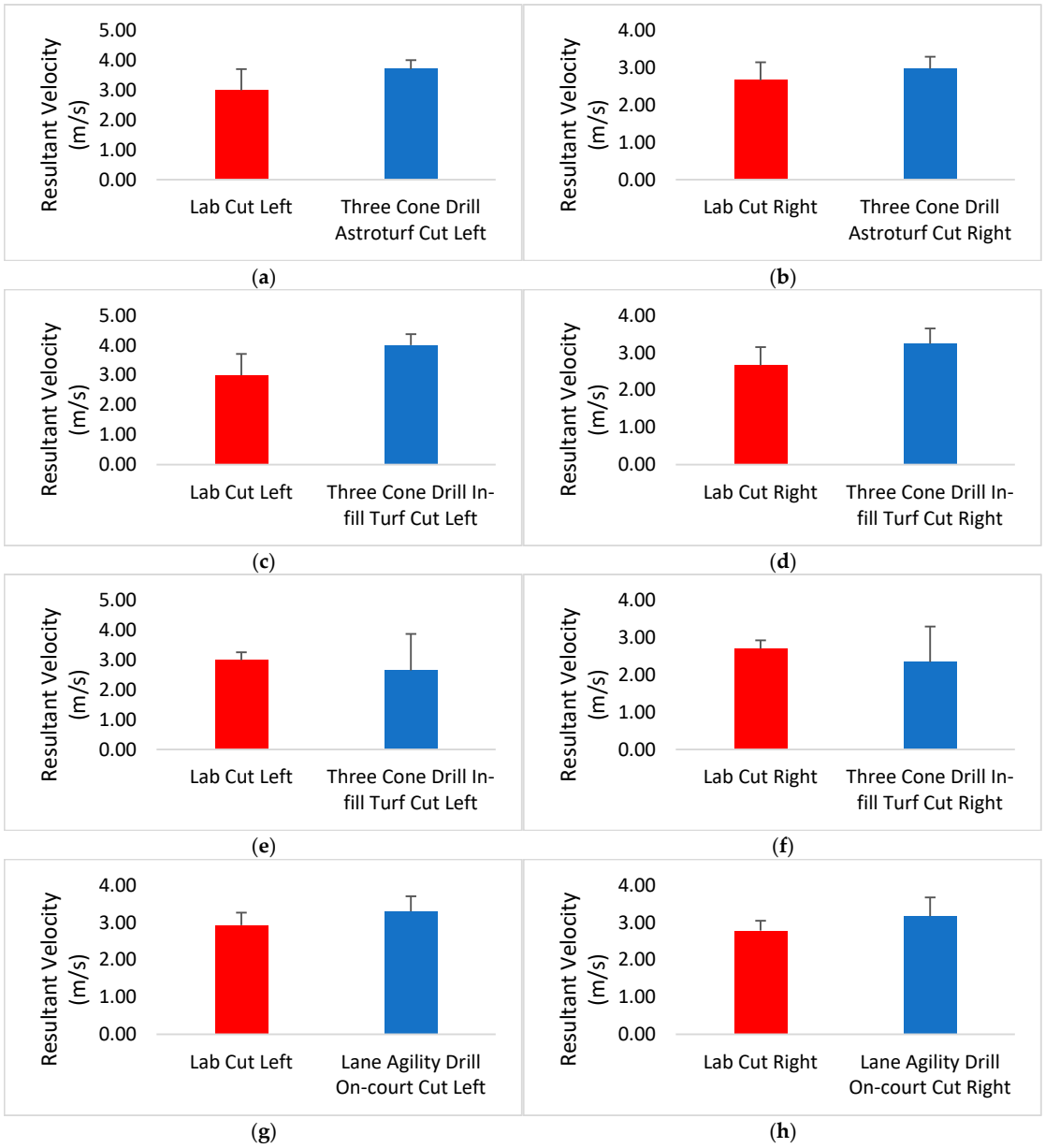


Figure 6. Mean comparison of CoM speed at initial contact during (**a**) a three-cone drill on the astroturf to the left and a cut left in lab from lacrosse athletes, (**b**) a three-cone drill on the astroturf to the right and a cut right in lab from lacrosse athletes, (**c**) a three-cone drill on the in-fill turf to the left and a cut left in lab from lacrosse athletes, (**d**) a three-cone drill on the in-fill turf to the right and a cut right from lacrosse athletes, (**e**) a three-cone drill on the in-fill turf to the left and a cut left in lab from soccer athletes, (**f**) a three-cone drill on the in-fill turf to the right and a cut right from soccer athletes, (**g**) a lane agility drill on-court to the left and a cut left in lab from basketball athletes, and (**h**) a lane agility drill on-court to the right and a cut right in lab from basketball athletes. Error bars are shown as standard deviation.

4. Discussion

The purpose of the current study was to quantify lower-extremity kinematics and compare them between sport-specific and laboratory environments in response to multiplanar

dynamic activities. The results presented here indicate that laboratory assessments may not replicate the demands of sport-specific movements. Knee joint kinematics were statistically different between the sport-specific and laboratory tasks.

Varsity lacrosse and basketball athletes had greater knee RoM performing the cutting maneuvers in their respective sport environments compared to the tasks performed in the laboratory. While soccer athletes did not have significant differences in knee RoM or speed, non-significance should not be interpreted as evidence that the two protocols produced equivalent kinematic demands. When on the field during a game or practice, athletes are required to adjust their movements in response to their teammates, opponents, ball, or other sporting equipment. Clinicians should recognize that controlled movement assessments may underestimate movement variability and demands encountered during sport. Chaudhari et al. [17] quantified an increase in knee joint valgus moment when participants performed an in-lab cutting task while holding a lacrosse stick compared to a baseline condition. Similarly, in a non-peer reviewed thesis, basketball athletes experienced greater knee RoM in the sagittal plane, in response to a 90° cutting task, in a clinical setting when compared to those that were performed on a court [18]. While not observed here when looking at the adjusted *p*-values, past research has also highlighted that the kinematic differences of volleyball athletes are dependent on the testing environment [19]. Knee flexion angle during the drop jump landing task performed in a laboratory environment was greater than the jump spike task performed while wearing augmented reality goggles simulating a game-like environment. Whether sport-environment kinematics improve injury risk assessment or post-injury RTS decisions remains to be tested in prospective studies of injured athletes [14].

The speed of the task performed by the individual may be another consideration when assessing athletes. In the current investigation, unadjusted *p*-values showed greater CoM speeds were achieved in the sport-specific environments compared to the lab, even with similar (5 m) approaching distances (Figure 6). While the results should be considered exploratory when using unadjusted *p*-values, one explanation for this is that there are space constraints in the lab (e.g., walls limiting the number of steps taken after changing direction from a cutting task) that are consistent with many laboratory and clinical settings. Statistical differences in knee joint mechanics as a function of approaching speed has been supported by previous work [20]. Previous research has suggested that collegiate level women's lacrosse athletes are reaching speeds of approximately 4.36 ± 0.67 m/s before changing direction [21]; most labs and clinics are unable to accommodate these pre-cutting speeds.

Another explanation for the approach speed differences is the interaction between footwear and surface and the alterations in friction [22]. Although friction was not measured in this study, one hypothesis is that the coefficient of friction between cleats and turf, as well as basketball shoes and hardwood, may be higher than between running shoes and laboratory flooring. This hypothesis requires direct measurement in future work. When comparing coefficient values of 0.78, 0.97, and 1.18 in basketball shoes, sprinting, jumping, and cutting, performance is worse when the coefficient is 0.78 compared to the two other conditions [23]. Previous research has also shown that the required coefficient of friction when performing a change of direction increases with increasing speed [24]. The speed of the lacrosse athletes with and without cleats was not statistically different. One possibility is that the coefficient of friction was similar to the laboratory condition, though this was not measured directly. While speed was not significantly different for soccer athletes, playing surfaces have been shown to influence ACL injury [25] with incidences of 1.16/10,000 athlete exposures on natural and 0.92/10,000 athlete exposures on artificial turf [26]. However, it is still inconclusive whether there are more injuries on artificial turf or natural grass as a recent systematic review suggested the rate of hip and knee injuries between the two

playing surfaces is similar [26]. Future research should continue to explore the effect of playing surfaces on the kinematics of common athletic movements.

There are limitations with the study that need to be considered. One limitation is that the lab and sport-specific tasks were intentionally kept different and, as a result, independent effects of environment were not isolated from task demands. The lab tasks (sidestep cut, stop jump) were selected because they represent standardized assessments commonly used in clinical injury risk screening and return-to-sport evaluation, while the sport-specific tasks (three-cone drill, lane agility drill, approaching jump) were selected because they reflect movement patterns athletes encounter during competition. This design prioritized the clinically relevant comparison (i.e., whether standard clinical assessments capture the kinematic demands of sport) over isolating the independent effect of environment. The findings can be interpreted as comparisons between commonly used clinical assessments and sport-specific movements.

Another limitation of the present study is that the marker-less motion capture used, while enabling field-based data collection, has lower accuracy in the frontal and transverse planes compared to the sagittal plane [8]. The paired within-subject design mitigates systematic measurement bias, as any consistent tracking offset cancels in the lab versus sport difference for each participant. However, random measurement noise increases within-subject variability and reduces statistical power, particularly for smaller nonsagittal effects. The smaller significant frontal and axial differences reported here should be interpreted cautiously, as they approach the expected measurement precision for these planes. Future studies should consider concurrent marker-based validation during sport-specific tasks to better characterize measurement precision in these conditions.

Also, even though knee kinematics of athletes were obtained in a sport-specific environment, the tasks performed were still quantified in a relatively controlled manner. The kinematics of athletes may be different during actual practices and games where the parameters of the movements are less structured. Future work should explore quantifying knee kinematics in practices and games, in real time, and whether a battery of tests with higher specificity can be recommended. Another limitation is that a limited number of athletes from only a limited number of sports were included in the study. Given the exploratory nature of the study, findings should be interpreted cautiously. While there are high rates of ACL injuries in the sports explored, athletes from other sports unfortunately also experience ACL injuries. Future work should explore athletes in more sports and compare the differences in all the athletes' return to sport.

5. Conclusions

The kinematic differences observed between sport-specific and laboratory tasks indicate that laboratory tasks may not reproduce the multiplanar knee demands of sport-specific movements. After Holm-Bonferroni correction, significant differences were concentrated in the frontal and transverse planes, predominantly for RoM, and were most consistent in lacrosse and basketball athletes. Surface, footwear, equipment, speed, and task changed together between protocols. The individual contribution of each factor cannot be determined from this design. The present findings are limited to healthy varsity athletes performing controlled sport-specific drills, and the sample includes neither prospective injury outcomes nor clinical RTS decision data. Whether the observed kinematic differences have clinical relevance for injury prevention or post-rehabilitation readiness assessment remains a question for future prospective validation in injured populations. Nonetheless, based on this study, clinically based movement assessments may not reproduce the kinematic demands observed during sport-specific tasks. It is important to consider task specificity when interpreting RTS assessments and screening results. This study quantified knee joint

kinematics and compared them between sport-specific tasks performed in the sporting environment and tasks performed in the laboratory. Athletes in different sports exhibited varying degrees of knee RoM depending on the environmental context. The kinematic differences reported here suggest that the testing protocol may influence movement assessment outcomes. Whether incorporating sport-specific testing improves injury risk identification or RTS decision-making requires prospective clinical validation in athletes undergoing rehabilitation. Future work should determine whether the kinematic differences observed here have clinical relevance for injury prevention and post-rehabilitation readiness.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of Variance
REDCap	Research Electronic Data Capture
ACLR	Anterior Cruciate Ligament Reconstruction
ACL	Anterior Cruciate Ligament
CoM	Center of Mass
DoF	Degree of Freedom
RoM	Range of Motion
RTS	Return to Sport
3D	Three Dimensional

Appendix A

Table A1. Comparison of F values, raw *p* values, adjusted *p* values, and 95% confidence intervals in the right and left knee during a three-cone drill on the astroturf to the left and a cut left in lab from lacrosse athletes, and a three-cone drill on the astroturf to the right and cut right in lab from lacrosse athletes.

Right Knee (Cut Left)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	4.92	0.077	0.696	−0.91	−12.07 [−26.06, 1.92]
Abd/Add IC	12.65	0.016	0.260	−1.45	−8.22 [−14.17, −2.28]
Int/Ext Rot IC	4.45	0.089	0.710	0.86	5.59 [−1.22, 12.40]

Table A1. *Cont.*

Flex/Ext 200ms	1.46	0.281	1.000	−0.49	−12.83 [−40.13, 14.47]
Abd/Add 200ms	0.53	0.498	1.000	0.30	2.70 [−6.80, 12.20]
Int/Ext Rot 200ms	8.05	0.036	0.509	1.16	14.06 [1.33, 26.80]
Flex/Ext RoM	2.98	0.145	1.000	−0.70	−6.87 [−17.10, 3.36]
Abd/Add RoM	41.63	0.001	0.027 *	−2.63	−10.33 [−14.44, −6.21]
Int/Ext Rot RoM	17.41	0.009	0.157	−1.70	−10.92 [−17.66, −4.19]
CoM Speed	22.19	0.005	0.100	−1.92	−0.94 [−1.46, −0.43]
Left Knee (Cut Right)					
Measure	**F**	**Raw *p* -Value**	**Adjusted *p* -Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	2.93	0.147	1.000	−0.70	−8.77 [−21.94, 4.39]
Abd/Add IC	6.88	0.047	0.563	1.07	6.95 [0.14, 13.77]
Int/Ext Rot IC	1.16	0.331	1.000	−0.44	−5.18 [−17.56, 7.20]
Flex/Ext 200ms	1.29	0.308	1.000	−0.46	−5.11 [−16.70, 6.48]
Abd/Add 200ms	7.99	0.037	0.509	1.15	10.43 [0.94, 19.92]
Int/Ext Rot 200ms	6.06	0.057	0.628	−1.01	−5.06 [−10.35, 0.22]
Flex/Ext RoM	0.42	0.548	1.000	−0.26	−2.71 [−13.54, 8.11]
Abd/Add RoM	8.45	0.033	0.502	−1.19	−11.57 [−21.80, −1.34]
Int/Ext Rot RoM	15.03	0.012	0.198	−1.58	−15.73 [−26.17, −5.30]
CoM Speed	5.51	0.066	0.657	−0.96	−0.44 [−0.92, 0.04]

* = denotes significance

Table A2. Comparison of F values, raw *p* values, adjusted *p* values, and 95% confidence intervals in the right and left knee during a three-cone drill on the in-fill turf to the left and a cut left in lab from lacrosse athletes, and a three-cone drill on the in-fill turf to the right and cut right in lab from lacrosse athletes.

Right Knee (Cut Left)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	3.38	0.116	1.000	−0.69	−9.97 [−23.24, 3.30]
Abd/Add IC	8.51	0.027	0.347	−1.10	−6.62 [−12.17, −1.07]
Int/Ext Rot IC	25.82	0.002	0.038 *	1.92	14.91 [7.73, 22.08]
Flex/Ext 200ms	0.11	0.751	1.000	−0.13	−1.77 [−14.79, 11.25]
Abd/Add 200ms	4.71	0.073	0.731	−0.82	−11.47 [−24.40, 1.47]
Int/Ext Rot 200ms	21.29	0.004	0.058	1.74	21.37 [10.04, 32.70]
Flex/Ext RoM	1.42	0.279	1.000	−0.45	−9.79 [−29.88, 10.31]
Abd/Add RoM	38.57	0.001	0.014 *	−2.35	−9.64 [−13.43, −5.84]
Int/Ext Rot RoM	7.23	0.036	0.418	−1.02	−13.84 [−26.44, −1.24]
CoM Speed	9.33	0.022	0.313	−1.15	−0.85 [−1.52, −0.17]

Table A2. *Cont.*

Left Knee (Cut Right)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	0.91	0.376	1.000	−0.36	−6.81 [−24.23, 10.61]
Abd/Add IC	0.70	0.434	1.000	0.32	2.59 [−4.96, 10.13]
Int/Ext Rot IC	0.90	0.379	1.000	0.36	3.38 [−5.34, 12.11]
Flex/Ext 200ms	0.68	0.441	1.000	0.31	4.39 [−8.63, 17.41]
Abd/Add 200ms	10.87	0.016	0.247	1.25	11.47 [2.96, 19.98]
Int/Ext Rot 200ms	0.56	0.484	1.000	−0.28	−3.04 [−13.01, 6.93]
Flex/Ext RoM	0.20	0.671	1.000	−0.17	−1.29 [−8.38, 5.79]
Abd/Add RoM	92.67	<0.001	0.001 *	−3.64	−11.55 [−14.48, −8.61]
Int/Ext Rot RoM	48.69	<0.001	0.008 *	−2.64	−14.73 [−19.90, −9.56]
CoM Speed	7.37	0.035	0.418	−1.03	−0.44 [−0.84, −0.04]

* = denotes significance.

Table A3. Comparison of F values, raw *p* values, adjusted *p* values, and 95% confidence intervals in the right and left knee during a three-cone drill on the in-fill turf to the left and a cut left in lab from soccer athletes, and a three-cone drill on the in-fill turf to the right and cut right in lab from soccer athletes.

Right Knee (Cut Left)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	0.99	0.343	1.000	0.30	4.26 [−5.28, 13.80]
Abd/Add IC	10.20	0.010	0.182	−0.96	−3.81 [−6.47, −1.15]
Int/Ext Rot IC	0.24	0.636	1.000	0.15	0.96 [−3.41, 5.33]
Flex/Ext 200ms	3.43	0.094	1.000	−0.56	−10.76 [−23.71, 2.18]
Abd/Add 200ms	9.01	0.013	0.239	−0.91	−6.69 [−11.66, −1.73]
Int/Ext Rot 200ms	14.41	0.004	0.070	1.14	10.40 [4.30, 16.51]
Flex/Ext RoM	0.03	0.860	1.000	0.05	0.73 [−8.22, 9.68]
Abd/Add RoM	1.08	0.323	1.000	−0.31	−1.25 [−3.92, 1.43]
Int/Ext Rot RoM	0.87	0.374	1.000	−0.28	−1.86 [−6.32, 2.60]
CoM Speed	0.97	0.349	1.000	0.30	0.35 [−0.44, 1.14]
Left Knee (Cut Right)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	0.62	0.451	1.000	0.24	5.26 [−9.67, 20.18]
Abd/Add IC	0.53	0.483	1.000	0.22	1.78 [−3.66, 7.21]
Int/Ext Rot IC	4.38	0.063	0.944	0.63	4.71 [−0.31, 9.73]
Flex/Ext 200ms	4.07	0.071	0.998	−0.61	−13.89 [−29.23, 1.45]

Table A3. *Cont.*

Abd/Add 200ms	6.23	0.032	0.507	0.75	3.32 [0.36, 6.28]
Int/Ext Rot 200ms	7.86	0.019	0.317	−0.85	−7.40 [−13.28, −1.52]
Flex/Ext RoM	0.04	0.850	1.000	0.06	0.90 [−9.47, 11.28]
Abd/Add RoM	2.23	0.166	1.000	0.45	2.09 [−1.02, 5.20]
Int/Ext Rot RoM	0.03	0.869	1.000	0.05	0.39 [−4.74, 5.51]
CoM Speed	1.24	0.291	1.000	0.34	0.55 [−0.55, 1.66]

Table A4. Comparison of F values, raw *p* values, adjusted *p* values, and 95% confidence intervals in the right and left knee during a lane agility drill on court to the left and a cut left in lab from basketball athletes, and a lane agility drill on court to the right and cut right in lab from basketball athletes.

Right Knee (Cut Left)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	0.00	0.965	1.000	−0.02	−0.22 [−13.39, 12.95]
Abd/Add IC	1.14	0.346	1.000	0.48	5.49 [−8.81, 19.79]
Int/Ext Rot IC	0.00	0.992	1.000	0.00	0.05 [−13.57, 13.67]
Flex/Ext 200ms	0.68	0.457	1.000	0.37	6.01 [−14.29, 26.32]
Abd/Add 200ms	7.42	0.053	0.686	1.22	15.35 [−0.30, 31.00]
Int/Ext Rot 200ms	0.22	0.665	1.000	0.21	3.59 [−17.74, 24.91]
Flex/Ext RoM	1.64	0.269	1.000	−0.57	−6.76 [−21.40, 7.89]
Abd/Add RoM	32.65	0.005	0.088	−2.56	−22.59 [−33.57, −11.62]
Int/Ext Rot RoM	11.92	0.026	0.416	−1.54	−25.47 [−45.95, −4.99]
CoM Speed	28.02	0.006	0.110	−2.37	−0.48 [−0.73, −0.23]
Left Knee (Cut Right)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	11.82	0.026	0.416	1.54	12.03 [2.32, 21.74]
Abd/Add IC	0.00	0.984	1.000	−0.01	−0.08 [−9.71, 9.56]
Int/Ext Rot IC	1.10	0.354	1.000	−0.47	−6.14 [−22.41, 10.13]
Flex/Ext 200ms	2.13	0.218	1.000	0.65	10.51 [−9.49, 30.50]
Abd/Add 200ms	3.82	0.122	1.000	−0.87	−4.92 [−11.91, 2.07]
Int/Ext Rot 200ms	0.00	0.982	1.000	−0.01	−0.11 [−12.81, 12.59]
Flex/Ext RoM	0.79	0.425	1.000	−0.40	−4.56 [−18.84, 9.72]
Abd/Add RoM	10.55	0.031	0.440	−1.45	−14.31 [−26.54, −2.08]
Int/Ext Rot RoM	59.33	0.002	0.031 *	−3.44	−22.81 [−31.03, −14.59]
CoM Speed	18.68	0.012	0.211	−1.93	−0.61 [−1.01, −0.22]

* = denotes significance.

Table A5. Comparison of F values, raw *p* values, adjusted *p* values, and 95% confidence intervals in the right and left knee during an approaching jump on court and a stop jump in lab from volleyball athletes.

Right Knee (Stop Jump)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	4.13	0.077	0.921	−0.68	−6.49 [−13.86, 0.88]
Abd/Add IC	0.26	0.622	1.000	0.17	0.33 [−1.17, 1.84]
Int/Ext Rot IC	4.59	0.065	0.839	0.71	4.26 [−0.33, 8.84]
Flex/Ext 200ms	6.41	0.035	0.562	−0.84	−10.74 [−20.51, −0.96]
Abd/Add 200ms	0.05	0.826	1.000	−0.08	−0.47 [−5.28, 4.33]
Int/Ext Rot 200ms	6.87	0.031	0.520	0.87	4.19 [0.50, 7.87]
Flex/Ext RoM	0.09	0.774	1.000	0.10	0.91 [−6.16, 7.98]
Abd/Add RoM	0.21	0.660	1.000	−0.15	−0.62 [−3.77, 2.52]
Int/Ext Rot RoM	3.95	0.082	0.921	−0.66	−2.00 [−4.33, 0.32]
Left Knee (Stop Jump)					
Measure	**F**	**Raw *p*-Value**	**Adjusted *p*-Value**	**d**	**Diff [95% CI]**
Flex/Ext IC	0.27	0.616	1.000	0.17	2.29 [−7.84, 12.43]
Abd/Add IC	5.26	0.051	0.714	−0.76	−1.64 [−3.29, 0.01]
Int/Ext Rot IC	0.03	0.875	1.000	0.05	0.44 [−5.85, 6.73]
Flex/Ext 200ms	5.50	0.047	0.705	−0.78	−12.74 [−25.27, −0.22]
Abd/Add 200ms	0.42	0.536	1.000	−0.22	−1.26 [−5.75, 3.23]
Int/Ext Rot 200ms	1.20	0.305	1.000	−0.37	−2.79 [−8.65, 3.07]
Flex/Ext RoM	2.07	0.188	1.000	0.48	8.11 [−4.88, 21.11]
Abd/Add RoM	4.10	0.078	0.921	−0.67	−2.05 [−4.38, 0.28]
Int/Ext Rot RoM	12.52	0.008	0.137	−1.18	−6.05 [−9.99, −2.11]

Table A6. Comparison of sport, plane, and outcome type based on significant results after adjusting the *p*-value.

Sport	**Outcome**	**Plane**	**Measure**	**Adjusted *p*-Value**
Lacrosse (In-fill)	IC	Transverse	R Int/Ext Rot IC	0.039
Lacrosse (In-fill)	RoM	Frontal	R Abd/Add ROM	0.014
Lacrosse (In-fill)	RoM	Frontal	L Abd/Add ROM	0.001
Lacrosse (In-fill)	RoM	Transverse	L Int/Ext Rot ROM	0.008
Lacrosse (Astroturf)	RoM	Frontal	R Abd/Add ROM	0.027
Basketball	RoM	Transverse	L Int/Ext Rot ROM	0.031

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