Master Thesis

Kinematics and performance of soccer players during the ‘change-of-direction t-test’

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Abstract PART I

Restoring movement quality after anterior cruciate ligament reconstruction is essential for a safe return to sport. While in-lab optical motion capture is currently considered the gold standard for movement quality analysis, it is lacking in ecological validity. This study served an exploratory purpose to investigate the effect of measurement surface on lower-limb kinematics and change-of-direction performance of healthy male soccer players. Fifteen healthy, male soccer players participated in this study. Movement data was collected with inertial measurement units attached to a suit (XSens LINK). Data was collected from participants performing the 'change-of-direction t-test' on three different surfaces: tartan of an indoor track, natural grass, and artificial turf. This study analyzed joint kinematics (°) of the hip, knee, and ankle joint in all three movement planes. Change-of-direction performance was quantified with mediolateral foot placement distance, change-of-direction velocity, and ground contact time. ANOVA Repeated Measures was used to analyze differences in joint angles at initial contact, peak joint angles, joint range of motion, and change-of-direction performance measures among measurement surfaces. Continuous joint analysis was performed with the repeated measures model of Statistical Parametric Mapping. During 90° change-of-direction maneuvers, lower ankle joint range of motion was found on the grass surface in the frontal movement plane ($p<0.030$). Next to that, ankle rotation angles at initial contact were significantly lower on the tartan surface ($p<0.036$). On the same surface, the ground contact time was longer ($p<0.047$) For the 180° change-of-direction sagittal plane range of motion of the ankle joint was significantly higher on tartan surface ($p<0.009$). Ankle rotation angles at initial contact were significantly lower on the tartan surface ($p<0.036$) Lastly, change-of-direction velocity was lower on turf surface ($p<0.001$). The differences among measurement surfaces suggest that measurement surfaces affect joint kinematics and change-of-direction performance of healthy male soccer players.

Abstract PART II

To bridge the gap between in-lab rehabilitation and complex team sports, on-field rehabilitation is increasingly offered to soccer players who underwent anterior cruciate ligament reconstruction. Currently, there is not yet consensus on sport-specific on-field test batteries to support return-to-play decision-making. This pilot study aimed to investigate the lower-limb kinematics and change-of-direction performance of soccer players after anterior cruciate ligament reconstruction. Eight, male soccer players participated in this study. Movement data was collected with inertial measurement units. Data was collected from participants performing the 'change-of-direction t-test'. Hip and knee joint angles were analyzed in sagittal and frontal movement plane. The paired t-test showed no significant differences in joint angles at initial contact, peak angles, and joint range of motion between the healthy and affected limb during both 90°and 180° change-of-direction maneuvers of the test. Next to that, no statistically significant differences in change-of-direction performance measures were found between healthy and affected limb. Though not significantly, participants turned tighter on the healthy limb than on the affected limb. This study suggests that change-of-direction tightness could be a parameter of interest when assessing change-of-direction performance in the future.

Acknowledgements

As the writer of this thesis, I have to acknowledge that I was not able to write this thesis without the help of several contributors.
First and foremost, I would like to thank professor Tuijthof. When I decided to ask you to sign my course list two years ago, I did not expect such a helpful hand in finding a thesis assignment that suited my study background and personal interests. During our weekly meetings, you have guided me through ethical reviews, method design, and result interpretation. Your enthusiasm for this project worked contagiously, always motivating me to go the extra mile.

I want to express my gratitude to Pro-F Professionele Fysiotherapie for providing me with hands-on clinical experience during both my internship and master assignment. It seems long ago that the idea for this thesis originated over a cup of coffee. Wouter, thank you for providing students like me the opportunity to learn in a clinically relevant environment. Suzan, thank you for showing me the ways of the performance lab. I really enjoyed working with you, conquering the weather conditions together, and sharing a mutual need for a second lunch or snack in the afternoon. Performing on-field measurements would not have been possible without the supervision of the on-field rehabilitation trainers. Rick, Youri, and Luuk, thank you for helping me.

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Completing this research within months would not have been possible without external help. Joey and Mark, I am really grateful for our collaboration. Thank you for setting up an assignment within the Zuyd University of Applied Sciences that facilitated the measurements on three different surfaces. Consequently, Suus en Iris, thank you for choosing and completing this assignment.

Thank you Liz for helping me perform the on-field measurements closer to home, in Enschede. Your bachelor assignment introduced and supported the idea of change-of-direction tightness as a performance measure.

Michiel, thank you for trusting me with the XSens equipment of the BDDP group.

Last but not least, I would like to thank Feike, the 'van Gasteltjes', the 'Blacq-jes', the 'van Veentjes', and the 'Koffieclub' for their constant support during my years as a student. You were always interested to hear stories about my research, though I have learned that I should refrain from talking about graft substitutes to some of you. Whilst this research finished somewhat late for the 'Kruisbandjes' in my family, I hope that this research contributes to a better understanding of the restoration of movement quality. In the future, maybe re-injury of the ACL can be prevented.

Contents

General introduction

Anterior cruciate ligament injuries are common in complex team sports such as soccer, frequently occurring during a decelerating 'change-of-direction' maneuver. [1] Injuries are followed by extensive rehabilitation to restore knee functioning and return to sport. [2] The end of the gym-based rehabilitation phase is often marked by an in-lab test battery consisting of muscular strength assessment and hop tests. [3]

On-field rehabilitation is advised to bridge the gap between gym-based rehabilitation and complex movements during soccer. The goal is to restore movement quality and physical conditioning, while gradually increasing the training load. [4] Sport-specific skills, such as sprinting, intermittent endurance, and agility are progressively introduced within training sessions. [1]

On-field testing allows the clinician to understand the physical fitness of the patient. Welling & Frik [1] and Forelli et al. [5] describe four criteria for an on-field test battery: repeated sprint ability, deceleration, intermittent endurance, and agility. Several on-field tests have been described in literature for each of these criteria. [6] Since most ACL injuries occur during a change-of-direction maneuver [7, 8], the focus in this research was on movement quality assessment during change-of-direction maneuvers.

While investigating change-of-direction tests described in literature, the 'change-of-direction t-test' and 'Illinois test' were most frequently mentioned. Upon comparison, the 'change-of-direction t-test' provides mainly two advantages. Firstly, the 'change-of-direction t-test' requires a smaller set-up area. Secondly, athletes cover a smaller distance to complete this test, making it less prone to fatigue when measured repeatedly. Consequently, the 'change-of-direction t-test' was selected as the investigative procedure.

Performance analysis during the 'change-of-direction t-test' is currently limited to the time required to complete the test. [9] Since timed performance is not affected by biomechanical deficits, [10] the current set-up of the 'change-of-direction t-test' lacks the ability to analyze movement quality.

The gold standard for movement quality analysis is in-lab optical motion capture. The setup for optical motion capture is expensive, not easily accessible, and holds spatial constraints. [11] Therefore, this method is not feasible for daily clinical practice. Inertial measurement units provide a relatively more accessible opportunity to measure rapid motion in sports. [11, 12] The clinical implementation of these sensors is still limited, resulting in a shortage of on-field movement quality analyses.

This research aims to bridge the gap between in-lab and on-field analysis of joint kinematics and change-of-direction performance. This thesis is split into two parts. In the first part, the effect of measurement surface on joint kinematics and change-of-direction performance in healthy soccer players during the 'change-of-direction t-test' is analyzed. The second part of this thesis aims to investigate what differences in joint kinematics and change-of-direction performance between healthy and affected limb are present during the on-field 'change-of-direction t-test' in soccer players after anterior cruciate ligament reconstruction. This thesis will be concluded by an overarching discussion.

PART I: The effect of measurement surface on performance of healthy soccer players during the 'change-of-direction t-test'

Introduction

Anterior cruciate ligament (ACL) injuries are common among complex field sports such as soccer. While internal risk factors (age, sex, anatomy) and external risk factors (shoe-surface interaction, motion perturbations) predispose an athlete, an ACL injury is preceded by a multi-planar inciting event, usually during lateral pivoting, a deceleration or landing maneuver. [1] During a typical inciting event for ACL injury, an athlete shows increased lateral trunk motion, externally rotated tibia, extended knee, and a deceleration followed by a valgus collapse. [2, 3] As a result of these kinematic factors, the strain on the ACL can exceed the mechanical tolerance, causing the ligament to tear. [4]

To regain mechanical stability of the knee joint and return to sport, athletes can undergo ACL reconstruction followed by an intensive rehabilitation period. The rehabilitation phase is completed in a gym-based environment. At the end of this phase, a hop test battery is conducted to determine whether a patient is ready to return to sport. [5] To bridge the gap between gym-based rehabilitation and returning safely to competition in soccer, on-field rehabilitation programs are increasingly offered. The focus of on-field rehabilitation lies on restoring movement quality, physical conditioning, and sport-specific skills, while gradually increasing the training load. [6]

Since altered movement quality increases the risk of secondary ACL injury, early identification and restoration of movement impairments is essential for a safe return to sport. [6] The 'change-of-direction T-test' provides a reliable and effective means for measuring preplanned change-of-direction ability. [7] At present, the performance of the on-field 'change of direction T-test' is quantified with the time required to complete the test. Yet, timed performance is not affected by biomechanical deficits and altered movement patterns. [8, 9]

Whereas laboratory-based optical motion capture is currently the gold standard for biomechanical analysis, drawbacks include its expensiveness and therefore accessibility. [10] Inertial measurement units (IMUs) are relatively more accessible when compared to optical motion capture. [11] These sensor units combine data from accelerometers, magnetometers, and gyroscopes to estimate sensor position in a global space, enabling the possibility for continuous on-field motion capture. [10, 12] Thus, utilization of IMUs allows qualitative and quantitative analysis of the 'change-of-direction t-test'

Change-of-direction performance can be quantified by mediolateral foot placement distance [13, 14], horizontal center of mass velocity [13, 15], and ground contact time [13, 16, 17]. Additionally, analyzing joint kinematics offers insights into qualitative aspects of change-of-direction performance. [17–19]

This study serves an exploratory purpose, aiming to analyze how measurement surface impacts joint angles and change-of-direction performance in healthy soccer players. To this author's knowledge, no research has been conducted into the effect of measurement surface on joint kinematics (°) and change-of-direction performance of healthy male soccer players during the 'change-of-direction t-test'.

This study hypothesizes that surfaces with a higher coefficient of friction of the shoe-surface interaction enable more optimal change-of-direction performance, due to less sliding [20], decreased ground contact time [20], and increased mediolateral foot placement distance [14]. The coefficient of friction can be defined as the ratio of shear forces to the vertical force [21] As a result of the increased coefficient of friction, the angle of the ground reaction forces can be directed more horizontally, allowing faster change-of-direction. [20, 22, 23]

Methods

This cross-sectional observational study investigated performance in the 'change-of-direction t-test' on three different surfaces. Data collection took place at the Zuyd University of Applied Sciences. This study is approved by the ethics committee of the University of Twente.

Participants

Soccer players were eligible for participation if they 1) were male, 2) were between 18-35 years old, 3) play soccer regularly (>2/week), and 4) did not have any injuries 6 months prior to the research. Participants were excluded if they 1) had a history of lower limb surgery, 2) suffered from ACL or meniscus injury, or 3) to their knowledge had any neurological or cardiac impairments. All participants signed an informed consent form.

Data collection

Participants wore the XSens LINK (Movella Technologies, Enschede, The Netherlands) lower-body set-up, consisting of eight inertial measurement units. An inertial measurement unit consists of 3D gyroscopes, accelerometers, and magnetometers. The overall sample rate was 240Hz. Each inertial measurement unit was placed using the designated positions on the LINK-suit: on the sternum, on the pelvis, on each upper leg, on each lower leg, and on each foot [24]. A schematic view of sensor placement locations is displayed in Figure 1. The system is calibrated according to the manufacturer's recommendation. For each measurement surface, the sensors were re-calibrated.

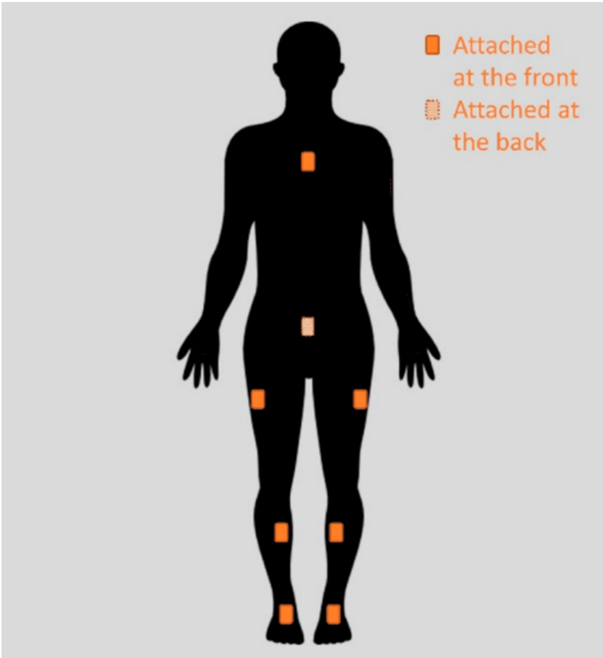
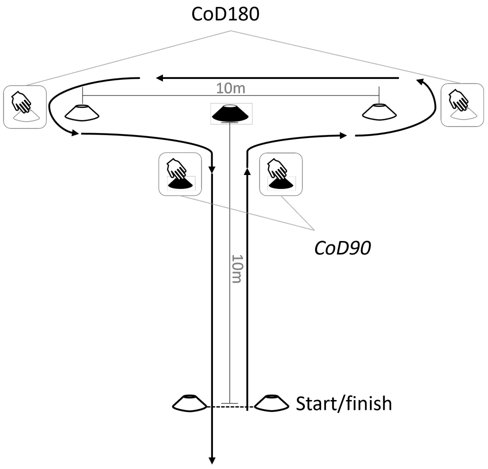


Figure 1: Sensor placement locations of the inertial measurement units, adapted from Huang et al. [25]

Procedures

The measurements are performed on tartan of an indoor track, natural grass, and artificial turf. A random order of measurement surfaces is selected for each participant to minimize the effects of fatigue. On the indoor track, participants wore running shoes. On the natural grass and artificial turf, all participants wore soccer cleats. After a brief warm-up, participants were orally instructed by the on-site investigator to complete the 'change-of-direction t-test' as fast as possible in a forward running pattern [26, 27].
A diagram of the 'change-of-direction t-test' is shown in Figure 2a. Each cone indicating a change of direction had to be tapped with a hand of choice, as denoted with a pictogram of a hand (Figure 2a). The 'change-of-direction t-test' includes two 90°change-of-direction maneuvers (CoD90) and two 180°change-of-direction maneuvers (CoD180). A participant during the CoD180 of the 'change-of-direction t-test' is shown in Figure 2b.



(a) Diagram of the 'change-of-direction t-test', running to the right.

(b) A participant during CoD180 of the 'change-of-direction t-test' on artificial turf wearing an XSens LINK suit

Figure 2: The 'change-of-direction t-test' displayed as a diagram (a) and a real-time example (b)

For each measurement surface, participants received one (unrecorded) practice trial in each direction for familiarization purposes. [27] Subsequently, data is collected during two trials in each direction. In between trials, the participant received a self-selected resting period for recovery. The measurements on all surfaces are performed in one session.

Data processing and statistical analysis

The primary outcome variables of this research are joint kinematics(°) [17–19] of the hip, knee, and ankle joint in sagittal, frontal, and transversal movement planes, the position of the center of mass relative to the foot [13, 14], change-of-direction velocity [13, 15], and ground contact time [16, 17, 19] during the CoD90 and CoD180. Analysis of the outcome variables is performed separately for CoD90 and CoD180.

Data is exported as a .mvnx file from XSens MVN (v2019.0, Movella Technologies, Enschede, The Netherlands) to a customized Matlab script (version R2023b, The Mathworks, Natick, US) for analysis. The commercially available Developer Toolkit 1.2.0 (Movella Technologies B.V., Enschede, The Netherlands) is used to extract segment, center of mass, and joint kinematic data of all three movement planes.
An algorithm is created to identify all change-of-direction maneuvers automatically during data analysis. Participants tapped each cone indicating a change-of-direction with a hand of choice. Therefore, change-of-direction maneuvers could be automatically identified based on drops in pelvis height. An example of automatic identification of change-of-direction maneuvers is shown in Figure 3.

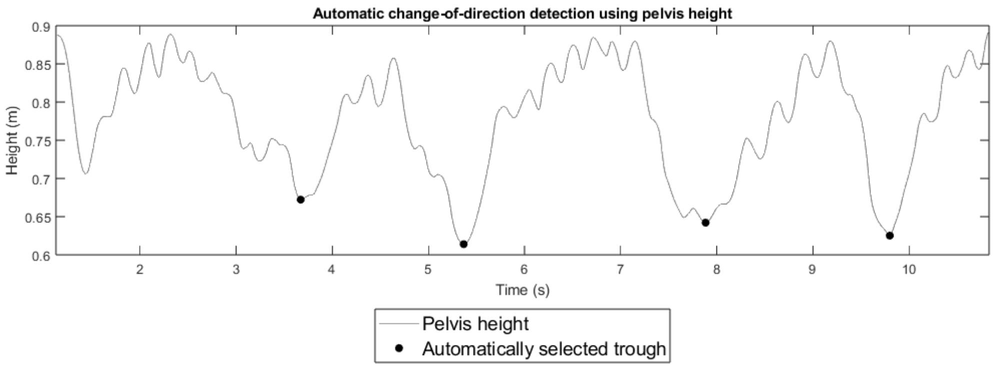
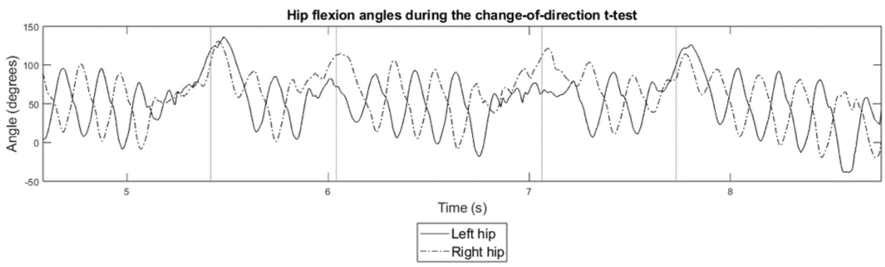
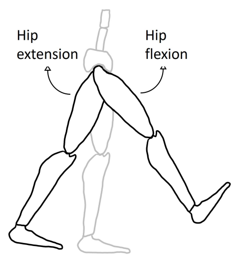


Figure 3: Automatic identification of change-of-direction maneuvers (black circle markers) based on pelvis height

Joint kinematics
Joint kinematic data of the hip, knee, and ankle joint is collected in sagittal, frontal and transversal movement plane. An example of sagittal plane hip angles during the 'change-of-direction t-test' is shown in Figure 4a. The four vertical lines correspond to the automatically detected change-of-direction maneuvers. In Figure 4b, a schematic illustration of hip flexion and hip extension is displayed.



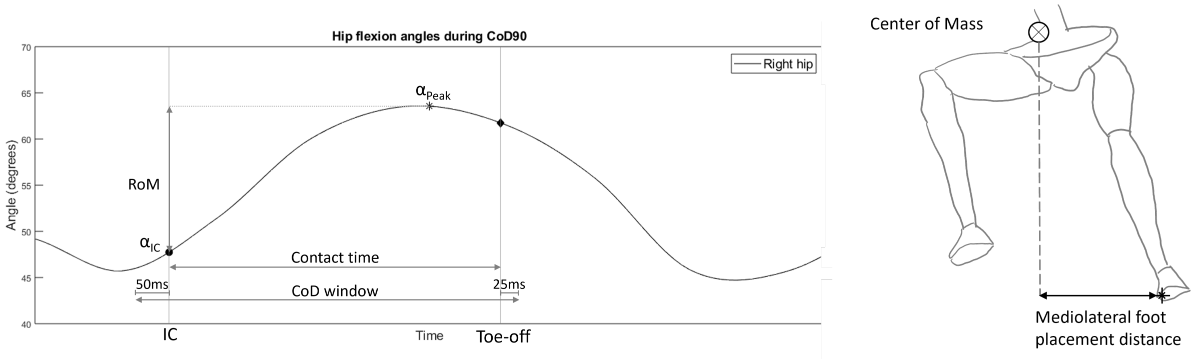
(a) Hip flexion angles during the 'change-of-direction t-test' of the left (dashed) and right (solid) hip. The identified change-of-direction maneuvers are indicated with the grey vertical lines.



(b) Hip flexion and extension in the sagittal movement plane

Figure 4: Sagittal plane movement of the hip

Discrete point analysis reduces the collected joint angle data to specific time points. [28] In this research, joint angles at initial contact, peak angles, and range of motion are analyzed during discrete point analysis. In Figure 5a, hip flexion angles during a CoD90 are shown. Initial contact (IC) is defined as the first contact of any part of the foot with the ground. Toe-off is defined as the last contact of any part of the foot with the ground. Change-of-direction windows are defined as 50ms before IC and 25ms after toe-off. [11] Joint angles are analyzed within the change-of-direction windows. The peak angle (α_{peak}) is the maximum joint angle within a change-of-direction window. For sagittal plane angles, the joint range of motion is defined as $Joint\ range\ of\ motion = \alpha_{peak} - \alpha_{IC}$, where α_{IC} is equal to the joint angle at initial contact. For frontal and transverse plane angles, the joint range of motion is defined as $Joint\ range\ of\ motion = \alpha_{peak} - \alpha_{min}$, where α_{min} is the minimal joint angle in the change-of-direction window.



(a) Hip flexion angles during 90°change-of-direction maneuver. Initial contact and toe-off are indicated with grey vertical lines. Joint range of motion (RoM) is the difference between the angle at initial contact and the peak angle. Ground contact time is defined as the time between initial contact and toe-off. Change-of-direction (CoD) window is defined as the time 50ms before initial contact to 25ms after toe-off.

(b) Schematic frontal view, where the horizontal distance between the center of mass and the foot is defined as mediolateral foot placement distance

Figure 5: Definition of a) Hip angles and b) mediolateral foot placement distance during a change-of-direction maneuver

Discrete joint data of each participant is averaged over the four attempts on each type of measurement surface and exported to IBM SPSS Statistics (Version 28.0. IBM Corp., Armonk, United States of America). The Kolmogorov-Smirnov test assessed the presence of normal distributions of the variables. The variances of the variables are assessed for equal spread with Mauchly's test of Sphericity. Discrete joint data are analyzed for statistical significance among measurement surfaces with ANOVA Repeated Measures. The significance level is adjusted for multiple comparisons with the Bonferroni-Holm procedure ($\alpha = 5\%$). [29, 30]
Kinematic data is originally collected as a continuous signal. Whereas discrete point analysis reduces the data to specific time points, continuous analysis aims to analyze entire movement curves. [28] Statistical Parametric Mapping (SPM) allows continuous analysis of entire movement curves for statistical significance. [28, 31] This research assessed joint angles among the three measurement surfaces continuously in a time-normalized interval (0%-100%) within the change-of-direction window through an ANOVA Repeated Measures model in SPM. The resulting output of SPM, an F-map, shows a time series of F-values. [32] Therefore, SPM can be used to find significant differences among measurement surfaces for regions in the movement curve. [33] The level of significance is $\alpha = 5\%$.

Change-of-direction performance
Change-of-direction performance is quantified with mediolateral foot placement distance [13, 14], change-of-direction velocity [13, 15], and ground contact time [16, 17, 19] Mediolateral foot placement distance is defined as the horizontal distance between the center of mass and the foot at IC, as shown in Figure 5b. [34] Change-of-direction velocity is defined as the minimal horizontal velocity of the center of mass within a change-of-direction window. [15, 35] Ground

contact time is defined as the time from IC to toe-off, indicated in Figure 5a.
The Kolmogorov-Smirnov test assessed the presence of normal distributions of the variables. The variances of the variables are evaluated for equal spread with Mauchly's test of Sphericity. Change-of-direction performance measures are analyzed for statistical significance among measurement surfaces with ANOVA Repeated Measures. The significance level is adjusted for multiple comparisons with the Bonferroni-Holm procedure (alpha = 0.05). [29, 30]

Results

Fifteen amateur male soccer players participated in this study. Descriptive data of participants is displayed in Table 1.

Table 1: Average and standard deviation of descriptive data of participants

	Age (years)	Length (cm)	Weight (kg)
Mean ± SD	21 ± 4.1	183.3 ± 7.0	72.3 ± 11.1

Change-of-direction maneuvers were identified based on drops in pelvis height indicating the tapping of a cone. The algorithm could successfully detect all change-of-direction maneuvers except for a single trial of one of the participants, which is shown in Figure 6.

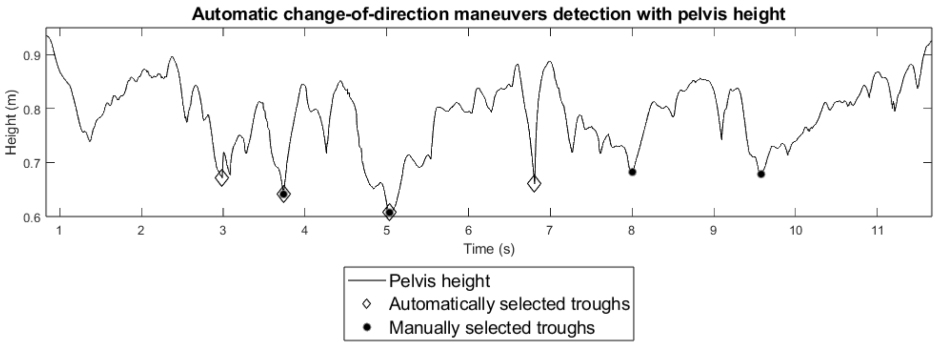
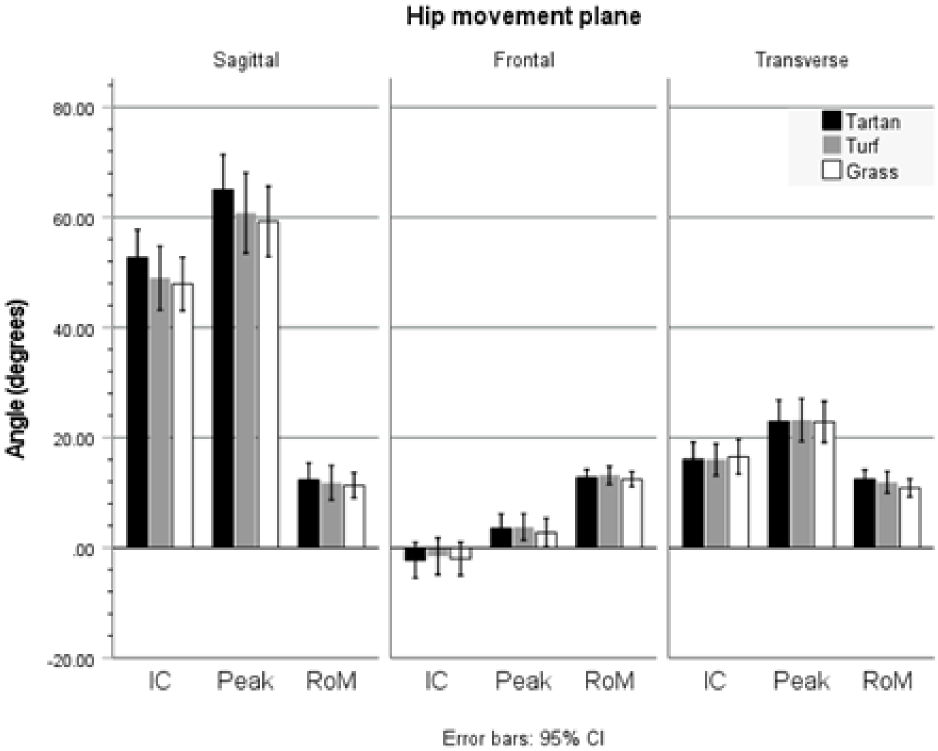


Figure 6: Wrongful automatic identification (diamond markers) of change-of-direction maneuvers during the 'change-of-direction t-test' using pelvis height. Manually selected troughs are indicated with filled circle markers.)

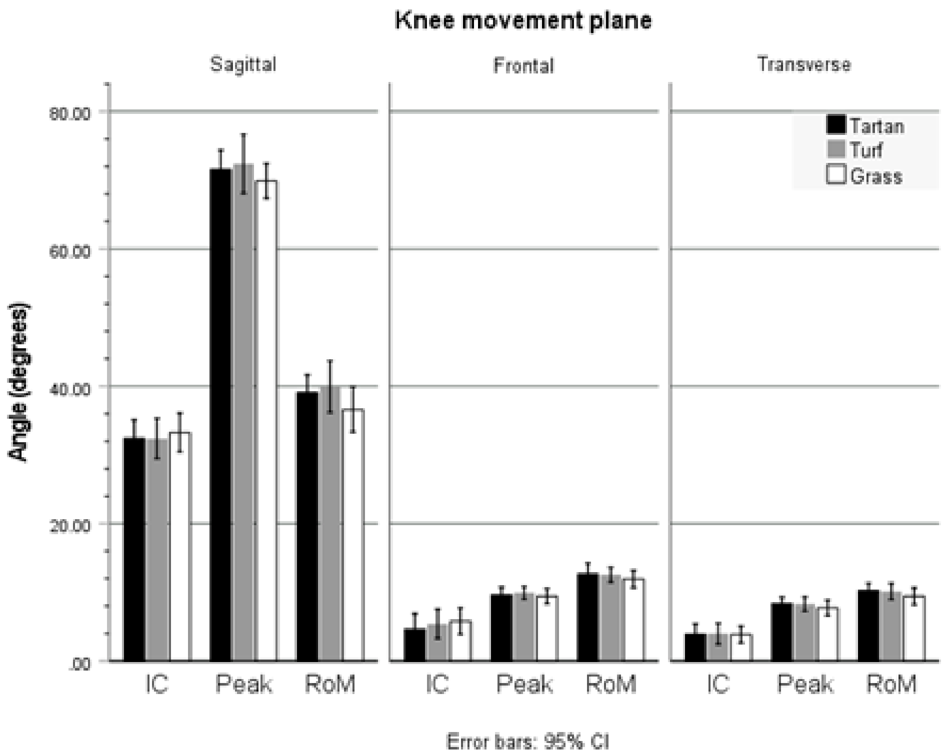
For this specific attempt, the change-of-direction maneuvers were manually identified based on visual inspection in MVN Analyze.

Joint kinematics

90° change-of-direction
Results of Kolmogorov-Smirnov test and Mauchly's test of Sphericity are shown in Table A1 in Appendix A. The Kolmogorov-Smirnov test showed hip frontal plane angles at IC, peak hip transverse plane, knee transverse plane at IC, and transverse plane ankle range of motion were not normally distributed. Mauchly's Test of Sphericity showed that peak frontal plane ankle angles did not show equal spread of differences. Results of discrete joint analysis are shown in Figure 7.

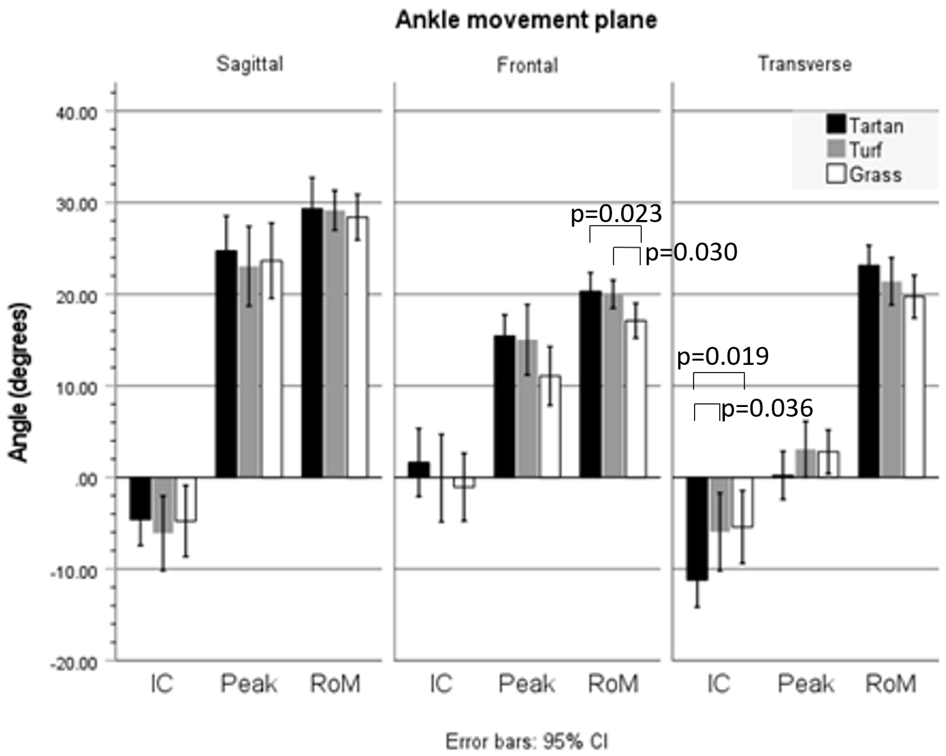


(a) Hip joint



(b) Knee joint

Figure 7: Results of discrete joint analysis for a) hip joint, b) knee joint, c) ankle joint during 90° change-of-direction. Results are presented as mean and standard deviations. Significant differences among measurement surfaces have been found in transverse movement plane of the ankle joint.

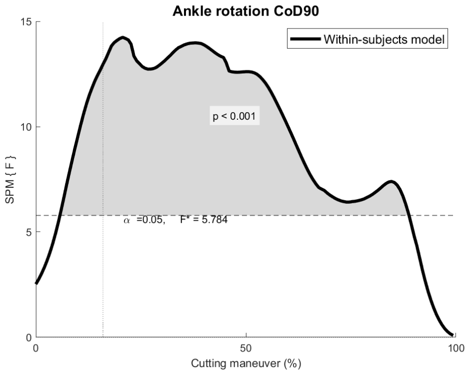


(c) Ankle joint

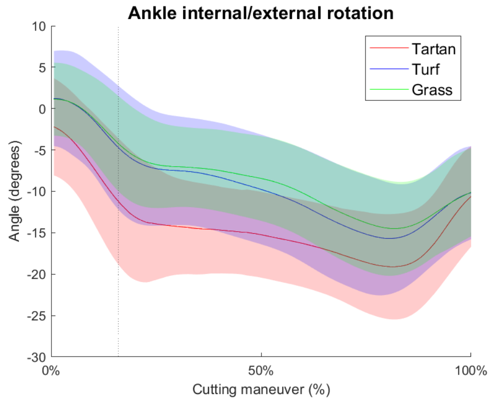
Figure 7: (continued) Results of discrete joint analysis for a) hip joint, b) knee joint, c) ankle joint during 90° change-of-direction. Results are presented as mean and standard deviations. Significant differences among measurement surfaces have been found in transverse movement plane of the ankle joint.

ANOVA Repeated Measures showed significant differences in the frontal plane ankle range of motion and transverse plane ankle angles at initial contact among measurement surfaces, as indicated in Figure 8c. For the ankle joint in frontal movement plane, post hoc analysis showed that the joint range of motion on tartan (20.2 ±3.7°) and turf (20.0 ±2.8°) were higher (p=0.023, and p=0.030 respectively) than on grass surface (17.1 ±3.4°). For the ankle joint in transverse movement plane, post hoc analysis showed that α_{IC} on turf (-5.9 ±7.7°) and grass (-5.4 ±7.2°) were higher (p=0.036, and p=0.019 respectively) than on tartan surface (-11.2 ±5.3°). All other discrete joint data showed no significant differences among measurement surfaces. For detailed numerical results of discrete joint analysis, please refer to Table A2 in Appendix A.

Continuous joint analysis showed significant differences in transverse plane ankle angles ($p<0.001$). Figure 8a displays the continuous F-values, the horizontally dashed line depicts the critical value. The grey area under the curve shows the regions of the change-of-direction maneuver where significant differences among measurement surfaces have been found. The mean and standard deviation for continuous ankle joint angles in the frontal movement plane are shown in Figure 8b.



(a) Results of continuous analysis for transverse plane ankle angles during 90° change-of-direction maneuver. The bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistically significant differences have been found among measurement surfaces



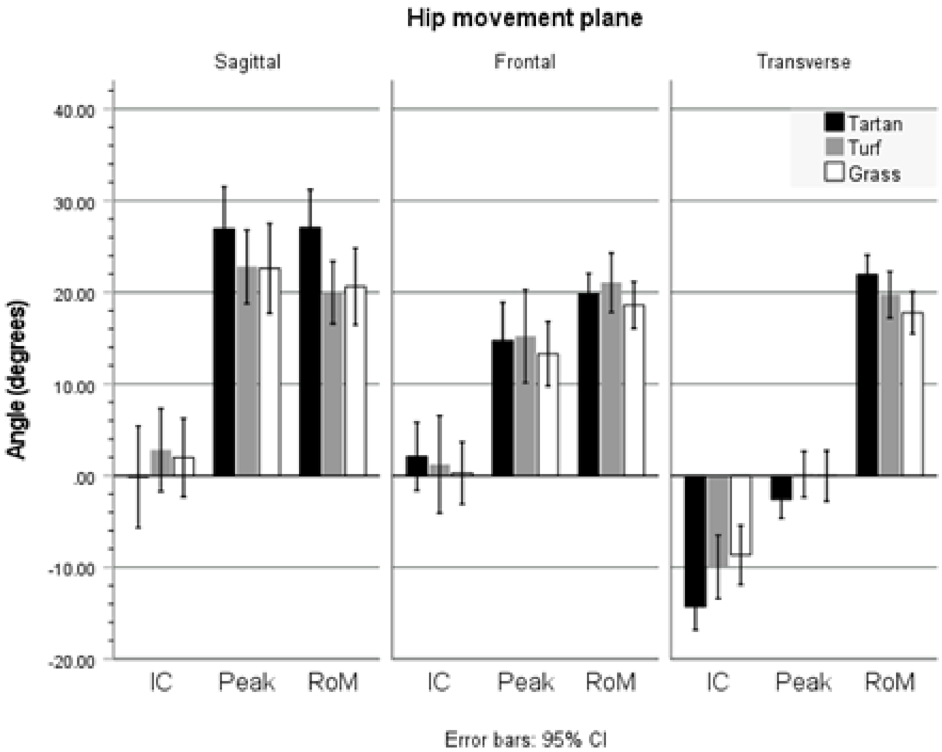
(b) Mean and standard deviation of transverse plane ankle angles during 90° change-of-direction on tartan (red), artificial turf (blue), and natural grass (green) surface. The vertical dotted line represents initial contact.

Figure 8: Differences in ankle transverse plane angles during CoD90 among three different measurement surfaces

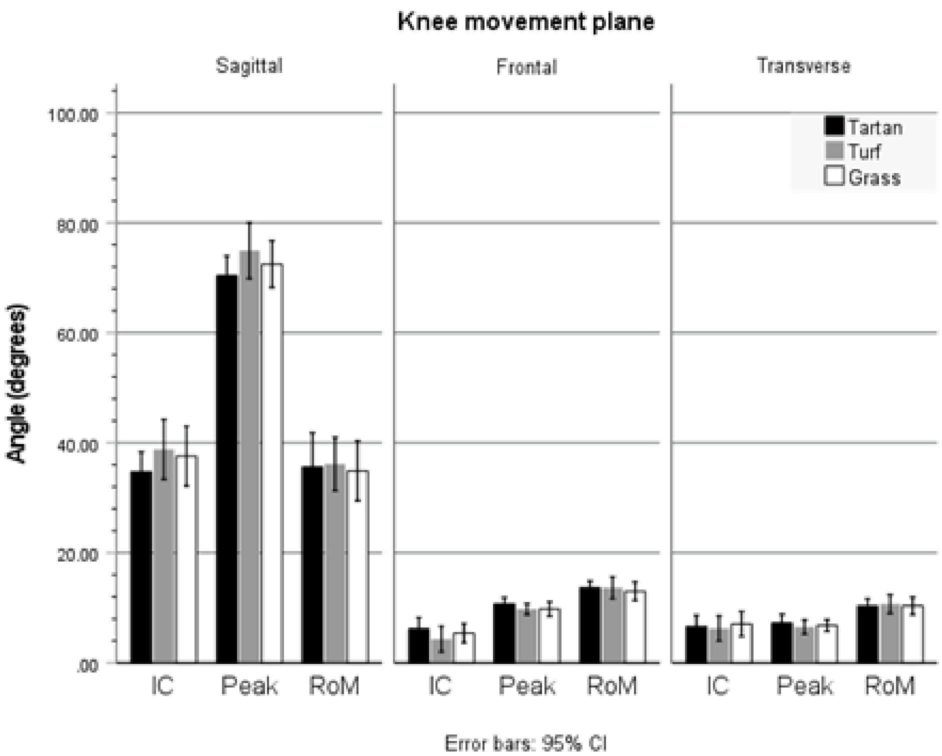
For all other movement curves, continuous joint analysis showed no statistically significant differences among measurement surfaces. Results of statistical parametric mapping for all joints and movement planes are presented in Figure C1, C2,and C3 in Appendix B.

180° change-of-direction

Results of Kolmogorov-Smirnov test and Mauchly's test of Sphericity are shown in Table C1 in Appendix C. The Kolmogorov-Smirnov test showed that sagittal plane hip range of motion, frontal hip angles at initial contact, and all discrete hip data in the transverse plane were not normally distributed. Mauchly's Test of Sphericity showed that frontal plane hip range of motion did not show an equal spread of differences. Results of discrete joint analysis are shown in Figure 9.

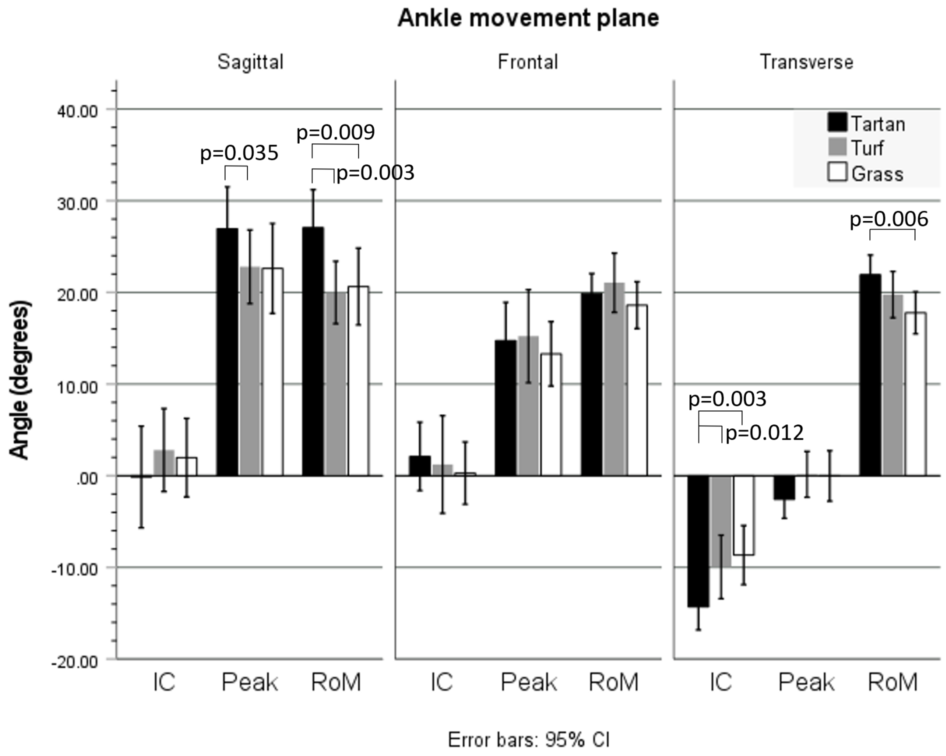


(a) Hip joint



(b) Knee joint

Figure 9: Results of discrete joint analysis for a) hip joint, b) knee joint, c) ankle joint during 180° change-of-direction. Results are presented as mean and standard deviations. Significant differences among measurement surfaces have been found in sagittal and transverse movement plane of the ankle joint.

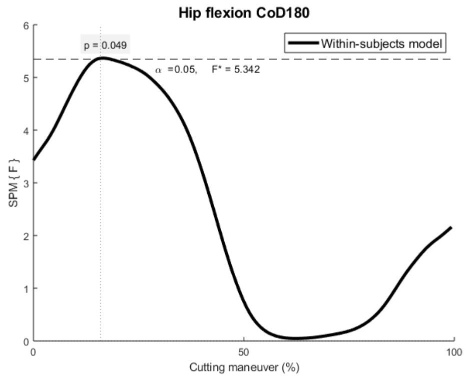


(c) Ankle joint

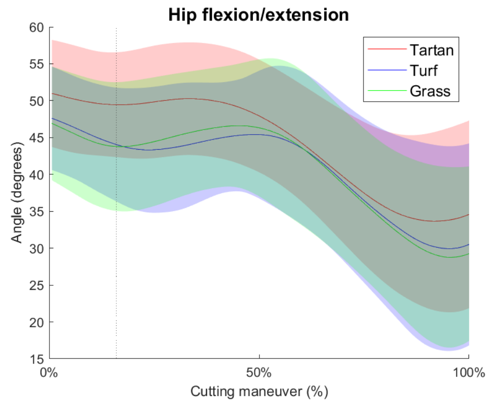
Figure 9: (continued) Results of discrete joint analysis for a) hip joint, b) knee joint, c) ankle joint during 180° change-of-direction. Results are presented as mean and standard deviations. Significant differences among measurement surfaces have been found in sagittal and transverse movement plane of the ankle joint

ANOVA Repeated Measures showed significant differences among measurement surfaces for the ankle joint in the frontal and transverse plane range of motion, sagittal plane peak angle, and transverse plane angle at initial contact, as indicated in Figure 10c. For the ankle joint in sagittal movement plane, post hoc analysis showed that the peak angle on tartan (27.0 ± 8.2°) was significantly higher (p=0.035) than on turf (22.8 ± 7.2°). For ankle joint range of motion in sagittal movement plane, post hoc analysis showed that the joint range of motion on tartan (27.1 ± 7.5°) was significantly higher (p=0.003, and p=0.009 respectively) than on turf (20.0 ± 6.2°) and grass surface (20.6 ± 7.6°). For the ankle joint in transverse movement plane, post hoc analysis showed that the angle at initial contact on tartan (-14.3± 4.5°) was significantly lower (p=0.012, and p=0.003 respectively) than on turf (-9.9 ± 6.3°) and grass (-8.7 ± 5.8°). For ankle joint range of motion in transverse movement plane, post hoc analysis showed that the joint range of motion on tartan (21.9 ± 3.9°) was significantly higher (p=0.006) than on grass (17.8 ± 4.1°). All other discrete joint data showed no significant differences among measurement surfaces. For detailed numerical results of discrete joint analysis, please refer to Table C2 in Appendix C.

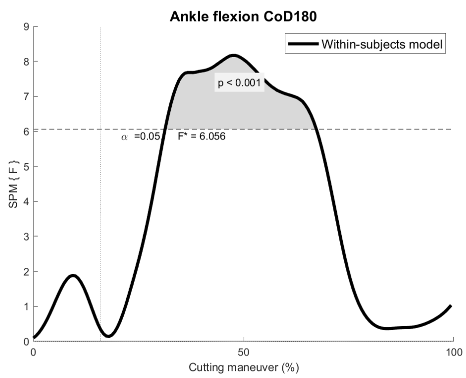
Results of continuous joint analysis are shown in Figure 10. Continuous F-values are shown in Figure 10a, 10c,and 11e. The horizontally dashed line depicts the critical value. The grey area under the curve shows the regions of the change-of-direction maneuver where significant differences among measurement surfaces have been found. Figure 10b, 10d, and 11f display mean and standard deviation of joint angles during the change-of-direction window for the measurement surfaces.



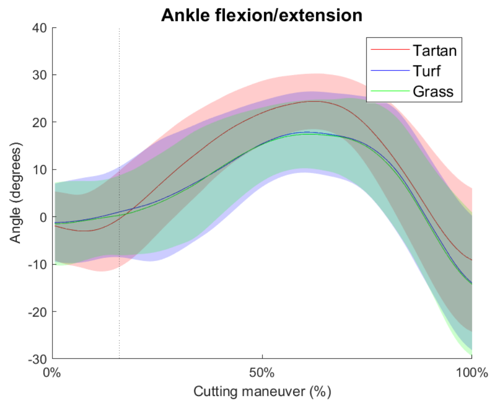
(a) Results of continuous analysis for sagittal plane hip angles during 180° change-of-direction maneuver. The bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistical significant differences have been found among measurement surfaces



(b) Mean and standard deviation for hip sagittal plane angles during 180° change-of-direction measured on tartan (red), turf (blue), and grass (green). Dotted vertical line indicates IC.

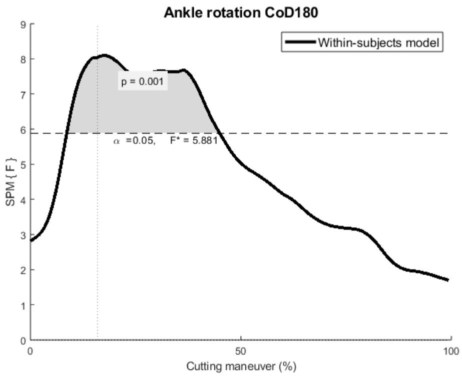


(c) Results of continuous analysis for sagittal plane ankle angles during 180° change-of-direction maneuver. The bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistical significant differences have been found among measurement surfaces

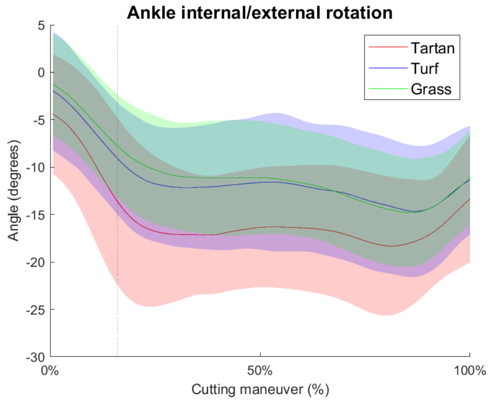


(d) Mean and standard deviation for ankle sagittal plane angles during 180° change-of-direction measured on tartan (red), turf (blue), and grass (green). Dotted vertical line indicates IC.

Figure 10: Results of continuous joint analysis



(e) Results of continuous analysis for transverse plane ankle angles during 180° change-of-direction maneuver. The bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistical significant differences have been found among measurement surfaces



(f) Mean and standard deviation for ankle transverse plane angles during 180° change-of-direction measured on tartan (red), turf (blue), and grass (green). Dotted vertical line indicates IC.

Figure 10: (continued) Results of continuous joint analysis

Continuous joint analysis showed significant differences in hip sagittal plane angles (p=0.049) (Figure 10a), ankle sagittal angles (p<0.001)(Figure 10c), and ankle transverse plane angles (p=0.001) (Figure 11e).
For all other movement curves, continuous joint analysis showed no statistically significant differences among measurement surfaces. Results of continuous joint analysis for all joints and movement planes are presented in Figure D1, D2, and D3 in Appendix D.

Change-of-direction performance

Results of ANOVA Repeated Measures for change-of-direction performance measures are presented in Table 2.

Table 2: Results of ANOVA repeated measures of change-of-direction performance measures

Performance measure	Tartan surface (mean ± SD)	Turf surface (mean ± SD)	Grass surface (mean ± SD)	p-value
90° change-of-direction				
Mediolateral foot placement distance (m)	0.37 ± 0.07	0.40 ± 0.07	0.41 ± 0.07	0.030
Change-of-direction velocity (m/s)	1.99 ± 0.40	2.20 ± 0.46	2.11 ± 0.45	0.027
Ground contact time (s)	0.40 ± 0.05	0.36 ± 0.05	0.36 ± 0.05	0.002*
180° change-of-direction				
Mediolateral foot placement distance (m)	0.33 ± 0.02	0.35 ± 0.02	0.35 ± 0.03	0.910
Change-of-direction velocity (m/s)	1.99 ± 0.10	1.08 ± 0.08	2.11 ± 0.11	<0.001*
Ground contact time (s)	0.35 ± 0.02	0.35 ± 0.03	0.36 ± 0.02	0.132

* *Statistically significant*

90° change-of-direction
ANOVA Repeated Measures showed statistically significant differences among measurement surfaces for ground contact time. Ground contact time measured on the tartan surface (0.40 ± 0.05s) was higher (p=0.047, and p=0.012 respectively) than on artificial turf (0.36 ± 0.05s) and natural grass (0.36 ± 0.05s). After Bonferroni-Holm corrections, mediolateral foot placement distance and change-of-direction velocity showed no significant differences among measurement surfaces.

180° change-of-direction
ANOVA Repeated Measures showed statistically significant differences among measurement surfaces for change-of-direction velocity. Post hoc analysis showed that change-of-direction velocity on artificial turf (1.08 ± 0.08m/s) was lower (p<0.001, and p<0.001)) than on tartan (1.99 ± 0.10m/s) and natural grass (2.11 ± 0.11m/s). Ground contact time and mediolateral foot placement distance showed no significant differences among measurement surfaces.

Discussion

The effect of surface on movement of male soccer players during directional changes is unknown. To address this, the study analyzed joint kinematics and change-of-direction performance across three different surfaces. However, a small number of limitations should be considered.
First is the size of the study population is limited. All participants were recruited and measured within a period of ten weeks, which for this study implied May to July. The end of soccer season complicated the recruitment of participants since most soccer teams were not training regularly during the recruitment period. A small sample size increases the probability of Type II errors, leading to nonsignificant results. [36]
Second there is very limited details about shoe-surface interaction on these specific surfaces. The frictional properties of the measurement surfaces remain undetermined. Additionally, shoe wear was not standardized. No information is available on how participants perceived traction on each surface. Acquiring details about such parameters would contribute significantly to the interpretation of the obtained results.
Third is the analysis of movement during change-of-direction maneuvers within a parkour such as the 'change-of-direction t-test', where participants have to cover a distance of forty meters to complete the test. In this research, participants performed twelve trials of the 'change-of-direction t-test' at maximum effort within one measurement session. To minimize the overall effects of fatigue on the performance measure, the order of measurement surfaces was randomized for each participant. Ideally, three separate measurement sessions are performed for each measurement surface. However, this was practically not feasible for participants, due to time constraints.
Fourth is the restriction to analyzing preplanned movement only. The kinetics and kinematics of athletes resulting from preplanned change-of-direction maneuvers differ from those from unplanned change-of-direction maneuvers. [14, 37, 38] Therefore, these results are not directly translatable to unplanned change-of-direction maneuvers. Since soccer players respond to opponents and ball movement, most directional changes are in response to a stimulus. [5] Therefore, adding a stimulus to the set-up would increase ecological validity.
Fifth, within this research joint kinematics were assessed with discrete point analysis and continuous analysis in this study. Discrete point analysis requires the identification of specific time points within a movement curve. An advantage of using discrete point analysis is that the joint range of motion can be evaluated. All discrete joint data must be checked for normality and sphericity, before performing ANOVA Repeated Measures. Continuous analysis evaluates entire movement curves for statistical differences. Furthermore, this is a fast method to scan if any differences among measurement surfaces exist. However, a disadvantage of continuous analysis is that the joint range of motion cannot be assessed. While both methods complement each other, performing both types of analysis is somewhat redundant and results in a lot of data. By performing continuous analysis first, movements can be scanned for statistical differences. Once continuous analysis shows any differences, discrete joint analysis can be performed to quantify the differences.

For the CoD90, significant differences were found in the sagittal and transverse movement plane of the ankle joint. Ground contact time during CoD90 was higher on the tartan surface, potentially as a result of sliding of the shoe on the surface. [20] For the CoD180, significant differences in continuous joint kinematics among measurement surfaces have been found in the hip sagittal plane, ankle sagittal plane, and ankle transverse plane. Change-of-direction velocity during CoD180 was significantly lower for the turf surface compared to tartan and grass surface. A 180° change-of-direction maneuver requires a deceleration, body rotation, and acceleration in the opposite direction. The resultant velocity of the center of mass consists of a component parallel and perpendicular to the movement direction. To perform a 180° change-of-direction maneuver, the velocity component parallel to the movement direction must be reduced to zero before acceleration in the opposite direction. [17] However, the velocity component in the perpendicular direction is not necessarily equal to zero. Speculatively, participants experienced more grip on the turf surface. Playing surfaces with a higher coefficient of friction allows faster deceleration and acceleration for athletes. [39] The perception of less grip on tartan and natural grass could potentially have caused participants to take a wider turn, requiring less immediate braking forces. However the perception of grip was not included as a study parameter.

To conclude, differences in joint kinematics and change-of-direction performance have been found among measurement surfaces. Further investigation on a larger scale is required to investigate the effect of measurement surface on movement and change-of-direction performance in healthy soccer players, including the perception of grip as a study parameter. Adding a stimulus to the change-of-direction maneuver would further increase ecological validity.

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PART II: The effect of anterior cruciate ligament reconstruction on joint kinematics and change-of-direction performance during the on-field 'change-of-direction t-test' in soccer players

Introduction

Anterior cruciate ligament (ACL) injury is common in all levels of competition in soccer. [1] To regain mechanical stability of the knee joint, ACL reconstruction is the clinical standard for athletes aiming to return to sport. [2] Currently, the gold standard for return-to-sports decision-making is often based on isokinetic strength assessment, hop testing, and psychological readiness. [3] Since hop test batteries mostly evaluate straight movement, they are lacking in the assessment of sport-specific performance. [2, 4] Next to that, the tests are often not conducted in an ecologically valid environment. [5]

To bridge the gap between the gym-based rehabilitation environment and the competitive team environment, on-field rehabilitation is advised to reduce the risk of re-injury. [2] The goal of on-field rehabilitation is to prepare the athlete for the sport-specific demands of their sport by gradually increasing the training load and focusing on restoring movement quality, physical conditioning, and sport-specific skills. [4, 6] The end of the on-field rehabilitation program is marked by return-to-play decision-making, where the clinician evaluates whether a patient is ready for a gradual return to competitive match play.

Despite the increasing interest in on-field rehabilitation, there is still no consensus on sport-specific on-field test batteries for return-to-sport decision-making. The 'change-of-direction T-test' provides a reliable and effective method to measure change-of-direction ability on-field. [7] Currently, performance analysis of the 'change-of-direction T-test' is limited to completion time. However, completion time is not necessarily impacted by biomechanical deficits. [8] Since altered movement quality has been prospectively linked with secondary ACL injury, identification of movement impairments is essential for a safe return to play. [6]

Inertial measurement units can be utilized to assess movement quality on-field. These wearable sensors estimate joint and segment orientation relative to a global system. [9] Therefore, inertial measurement units can provide the clinician with valuable information about movement quality required for return-to-play decision-making

Few studies reported movement quality analysis of soccer players through inertial measurement units. King et al. [10] discovered biomechanical performance asymmetries during change-of-direction movements in multidirectional field athletes after ACL reconstruction. However, the change-of-direction movements were performed in a laboratory setting and are therefore lacking in ecological validity. Meanwhile, DiPaolo et al. [11] discovered altered lower-limb kinematic differences in healthy female soccer players during change-of-direction tasks between a laboratory and on-field setting, highlighting the importance of overcoming the lack of ecological validity in current sport-specific tests.

To our knowledge, no research has been conducted that measured lower-limb kinematic differences during the on-field 'change-of-direction T-test' in male soccer players after ACL reconstruction. Therefore, it remains unclear if male soccer players show movement deficits during on-field change-of-direction maneuvers. Given this existing knowledge gap, this pilot study serves an exploratory purpose. In this study, we propose to quantitatively measure lower extremity kinematics in patients after ACL reconstruction during the on-field 'change-of-direction T-test'.

Methods

This cross-sectional observational study investigated performance in the on-field 'change-of-direction t-test' in male soccer players rehabilitating from ACL reconstruction. The regional Medical Research Ethics Committee (MREC Oost-Nederland, RadboudUMC) evaluated this study as non-WMO-applicable (2024-17113).

Participants

Soccer players were eligible for participation if they 1) were male, 2) were between 18-32 years old, 3) played soccer regularly before injury ($>$ 2 sessions/wk), 4) underwent primary, uncomplicated ACL reconstruction in the past two years, 5) participated in the on-field rehabilitation program of Pro-F Professional Physiotherapy (Enschede, The Netherlands), and 6) had the ambition to return-to-competition. Participants were excluded if they 1) had a history of lower limb surgery, 2) suffered from bilateral ACL or meniscus injury, or 3) to their knowledge had any neurological or cardiac impairments. Participants were not screened for graft type. All participants signed an informed consent form.

Data collection

Participants wore an XSens MTw-2 Awinda (Movella Technologies, Enschede, The Netherlands) lower-body set-up, consisting of eight inertial measurement units. An inertial measurement unit includes 3D gyroscopes, accelerometers, and magnetometers. The overall sample rate was 100Hz. Each inertial measurement unit is placed using Velcro body straps in accordance with the sensor placement guide, as shown in Figure 11: on the sternum, on the pelvis, on each upper leg, on each lower leg, and on each foot [12]. The system is calibrated according to manufacturers' recommendations.

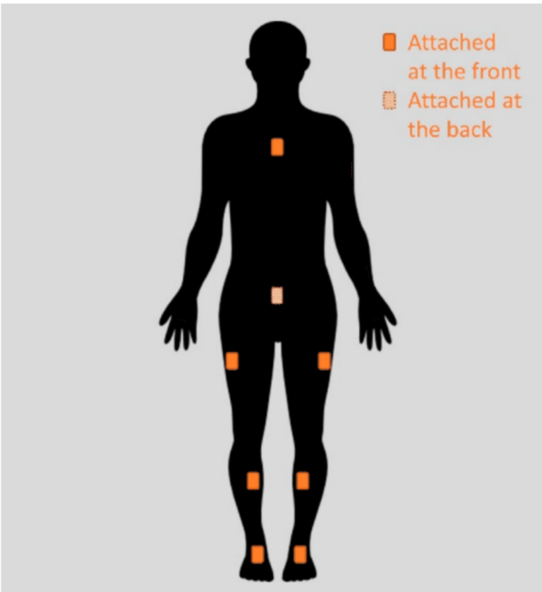
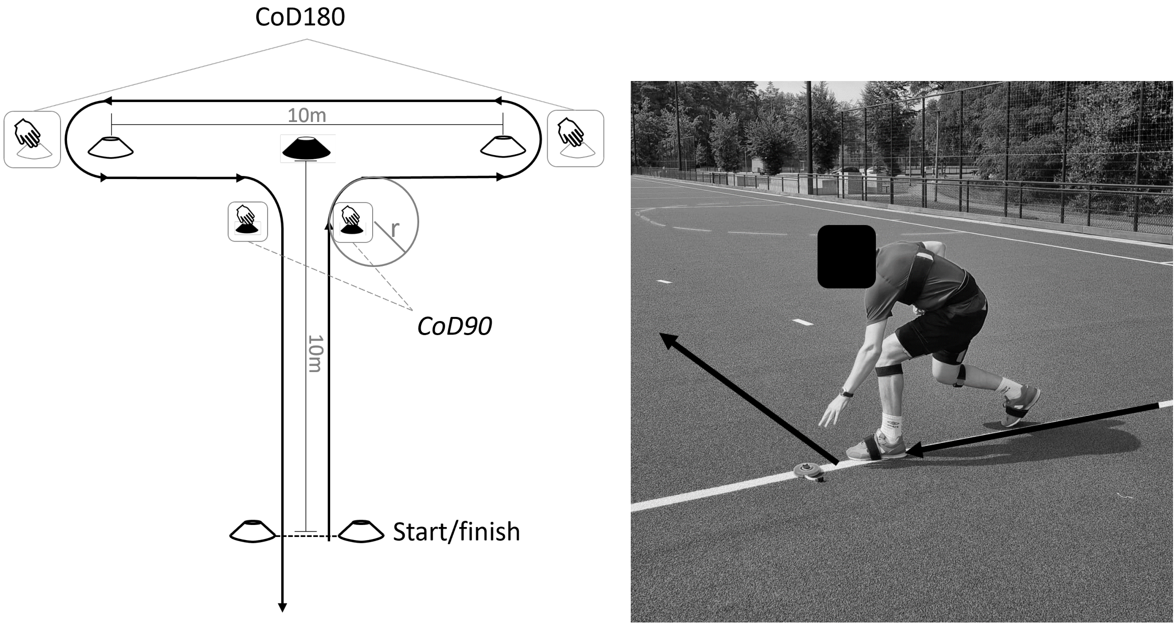


Figure 11: Positions of sensors of the MTw Awinda lower-body set-up, adapted from Huang et al. [13]

Completion time is measured using a single WittyGate (MicroGate Srl, Bolzano, Italy) photocell at the starting/finish line. Participants completed the ACL-RSI to assess psychological readiness to return to sport. [14]

Procedures

The measurements are performed on artificial turf. All participants wore soccer cleats. After a ten-minute warm-up led by a physiotherapist, participants were orally instructed by the on-site investigator to complete the 'change-of-direction t-test' as fast as possible in a forward running pattern [15, 16]. The 'change-of-direction t-test' consists of a T-shaped course, where participants perform two 90°change-of-direction maneuvers (CoD90) and two 180°change-of-direction maneuvers (CoD180). A diagram of the 'change-of-direction t-test' is shown in Figure 12b. Each cone indicating a change of direction had to be tapped with a hand of choice (Figure 12b).



(a) Diagram of the 'change-of-direction t-test' to the right, consisting two 90°change-of-direction maneuvers (CoD90) and two 180°change-of-direction maneuvers (CoD180). The black arrows represent the course route for the rightward 'change-of-direction t-test'. The grey circle represents a measure for change-of-direction tightness, as explained in section 'Data processing and Statistical analysis'.

(b) An athlete completing an CoD90 of the 'change-of-direction t-test' on artificial turf while wearing the XSens MTw Awinda sensors. The black arrows correspond with the course route.

Figure 12: 'Change-of-direction t-test' to the right

Participants received one (unrecorded) practice trial in each direction for familiarization purposes [16]. Data is collected during two trials in each direction. In between trials, the participant received two minutes of rest for recovery. After the last trial, participants filled out the ACL-RSI and resumed the on-field rehabilitation session.

Data processing and statistical analysis

Primary outcome variables of this research are joint kinematics and change-of-direction performance during the CoD90 and CoD180. Data is exported as an .mvnx file from XSens MVN (v2019.0, Movella Technologies, Enschede, The Netherlands) to a customized Matlab script (version R2023b, The Mathworks, Natick, US) for analysis. The commercially available Developer Toolkit 1.2.0 (Movella Technologies B.V., Enschede, The Netherlands) is used to extract segment, center of mass, and joint kinematic data of all three movement planes.
Participants tapped each cone indicating a change-of-direction with a hand of choice. Therefore, change-of-direction maneuvers could be automatically identified based on drops in pelvis height. An example of automatic identification of change-of-direction maneuvers is shown in Figure 13.

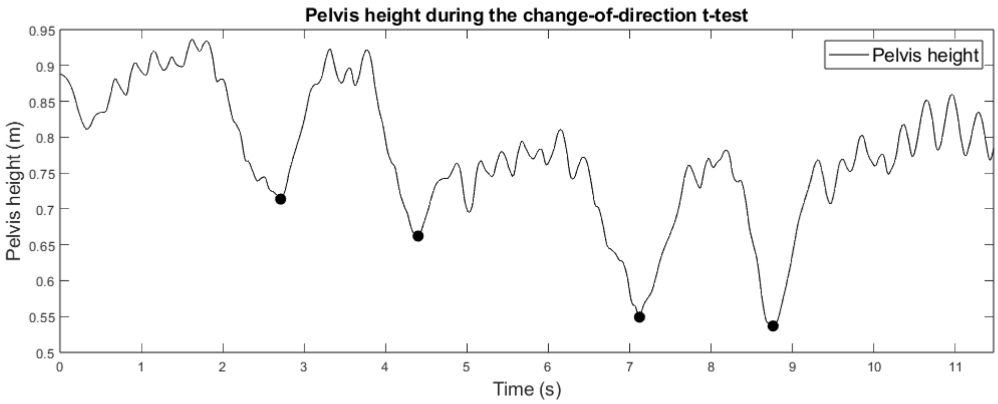
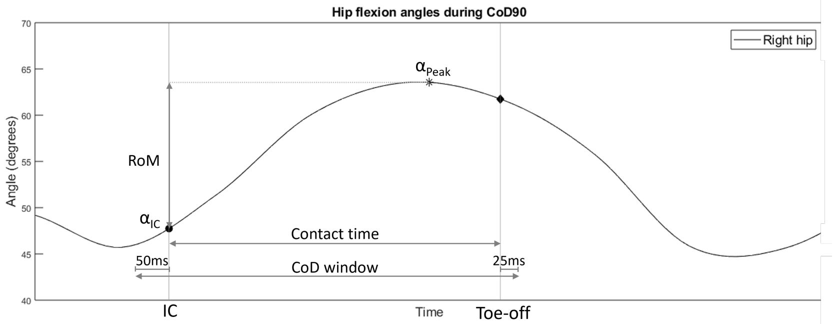


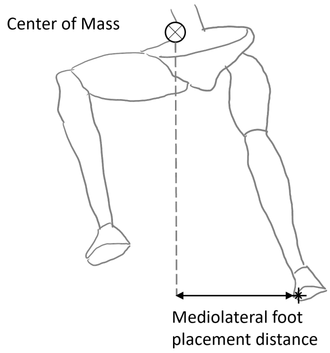
Figure 13: Automatic identification of change-of-direction maneuvers (black circle markers) based on pelvis height

Each participant completed the 'change-of-direction t-test' four times. Data of the healthy and affected limb is averaged for each participant.

Joint kinematics
Joint angles [17–19] of the hip and knee joint are analyzed in sagittal and frontal movement planes [10] during the CoD90 and CoD180. An example of sagittal hip angles during the 'change-of-direction t-test' is shown in Figure 4a in the Method section of Part I.
Discrete point analysis reduces joint angle data to specific time points. [20] In this research, joint angles at initial contact, peak angles, and range of motion are analyzed. In Figure 14a, hip flexion angles during a CoD90 are shown.



(a) Hip flexion angles during 90°change-of-direction maneuver. Initial contact and toe-off are indicated with grey vertical lines. Joint range of motion (RoM) is the difference between the angle at initial contact and the peak angle. Ground contact time is defined as the time between initial contact and toe-off. Change-of-direction (CoD) window is defined as the time 50ms before initial contact to 25ms after toe-off.



(b) Schematic frontal view, where the horizontal distance between the center of mass and the foot is defined as mediolateral foot placement distance

Figure 14: Hip angles (a) and mediolateral foot placement distance (b) during a change-of-direction maneuver

Initial contact (IC) is defined as the first contact of any part of the foot with the ground. Toe-off is defined as the last contact of any part of the foot with the ground. Change-of-direction windows are defined as 50ms before IC and 25ms after toe-off. [21] Joint angles are analyzed within the change-of-direction windows. The peak angle (α_{peak}) is the maximum joint angle within a change-of-direction window. For sagittal plane angles, the joint range of motion is defined as $Joint\ range\ of\ motion = \alpha_{peak} - \alpha_{IC}$ where α_{IC} is equal to the joint angle at IC. For frontal plane angles, the joint range of motion is defined as $Joint\ range\ of\ motion = \alpha_{peak} - \alpha_{min}$ where α_{min} is equal to the minimal joint angle in the change-of-direction window. Discrete joint data is exported to IBM SPSS Statistics (Version 28.0. IBM Corp., Armonk, United States of America). The discrete joint data are verified for normality with the Kolmogorov-Smirnov test and expressed as mean and standard deviation. A paired t-test is conducted to assess differences between the healthy and affected limb for normally distributed data. Wilcoxon's test is conducted to assess differences between the healthy and affected limb for non-normally distributed data. The significance level is adjusted for multiple comparisons with the Bonferroni-Holm procedure ($\alpha = 5\%$). [22, 23]

Change-of-direction performance
Change-of-direction performance is quantified with the mediolateral foot placement distance [24, 25], change-of-direction velocity [24, 26], and ground contact time [18, 19, 27]. In this study, another performance metric called 'change-of-direction tightness' is introduced and analysed.
The mediolateral foot placement distance is defined as the horizontal distance between the center of mass and the foot at initial contact, as shown in Figure 14b. [28] In this research, change-of-direction velocity is defined as the minimal horizontal velocity of the center of mass within the change-of-direction window. [26, 29] Ground contact time is defined as the time from IC to toe-off, indicated in Figure 5a.
For CoD90, 'change-of-direction tightness' can be described as the radius of a best-fit circle over the pelvis trajectory. [30] Figure 12b shows an example of a best-fit circle (grey). A larger radius (r) indicates a wider change-of-direction maneuver. For CoD180, 'change-of-direction tightness' can be described as the average distance between the in-going and out-going pelvis trajectory [30], as represented with the grey arrows in Figure 15.

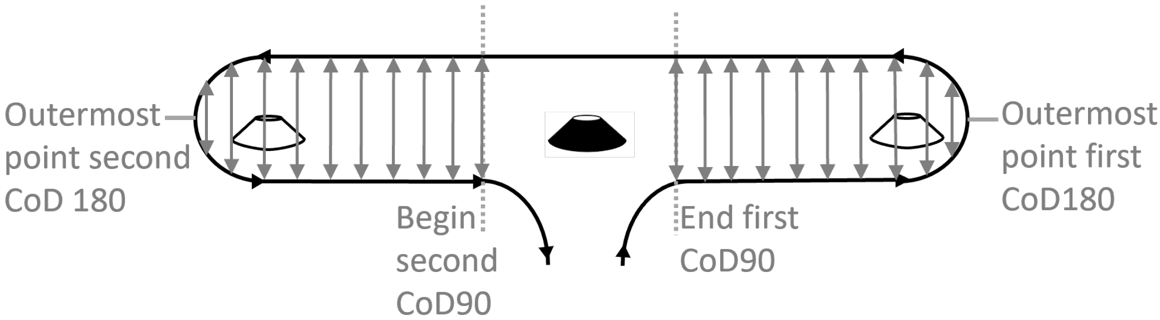


Figure 15: Schematic view of the top part of the 'change-of-direction t-test', where the grey arrows indicate the distance between the ingoing and outgoing path of the CoD180.

For the first CoD180, the average distance between the in- and outgoing paths is calculated for all time frames between the end of the first CoD90 to the outermost point of the first CoD180. For the second CoD180, the average distance between the in- and outgoing paths is calculated for all time frames between the outermost point of the second CoD180 and the beginning of the second CoD90. A larger distance between the in- and outgoing paths indicates a wider change-of-direction maneuver.
Average mediolateral foot placement distance, change-of-direction velocity, ground contact time, and change-of-direction tightness of the healthy and affected limb are verified for normal distributions using the Kolmogorov-Smirnov test in IBM SPSS Statistics (Version 28.0. IBM Corp., Armonk, United States of America). A paired t-test is conducted to assess differences between the healthy and affected limb for normally distributed data. Wilcoxon's test is conducted to assess differences between the healthy and affected limb for non-normally distributed data. The significance level is adjusted for multiple comparisons with the Bonferroni-Holm procedure ($\alpha = 5\%$). [22, 23]

Results

Eight amateur male soccer players participated in this study. The participants reported dominant leg (n=6 right) and affected leg (n=4 right). Descriptive statistics of participants are shown in Table 3.

Table 3: Descriptive statistics of participants

Descriptive	Mean ± SD
Age (years)	27 ± 3.5
Length (cm)	181 ± 5.0
Weight (kg)	79 ± 5.6
Time since ACL reconstruction (wks)	42 ± 13.2
On-field rehabilitation sessions (n)	6 ± 3.5
ACL-RSI score	87 ± 15.6
Timed performance (s)	10.1 ± 0.7

One participant only completed three trials of the change-of-direction t-test due to a feeling of discomfort in the hamstring muscles. For this participant, only the first trial of both directions was investigated. Time cells could not be included in the measurement setup for two participants, therefore these participants are not included in average timed performance.
Automatic identification of change-of-direction maneuvers results were poor. In Figure 16, pelvis height during the on-field 'change-of-direction t-test' is displayed. Change-of-direction maneuvers were identified manually through visual inspection in XSens MVN Analyze.

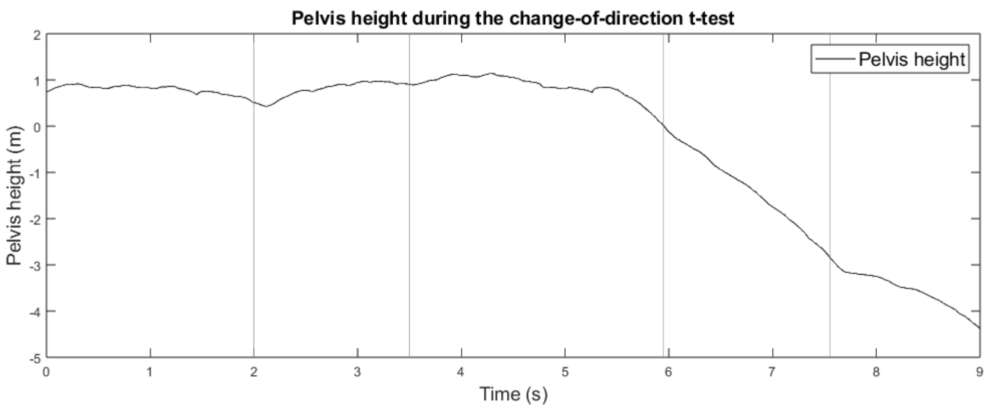


Figure 16: Failed automatic identifcation of change-of-direction maneuvers using pelvis height. Manually identified maneuvers are indicated with grey vertical lines

Joint kinematics

90° change-of-direction
Results of the Kolmogorov-Smirnov test are displayed in Table E1 in Appendix E. All discrete joint kinematic variables are normally distributed except for peak knee abduction angles (p=0.001). Results of discrete joint analysis are displayed Figure 17.

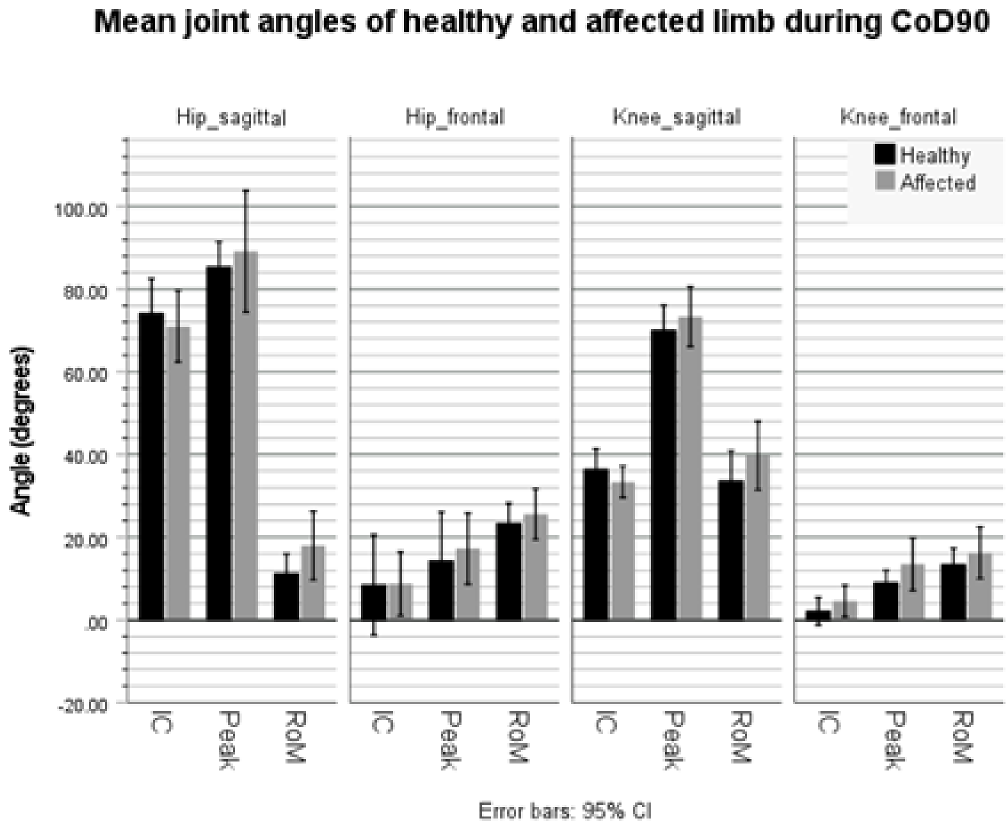


Figure 17: Results of discrete joint analysis during CoD90. Results are presented as mean and standard deviations. In the sagittal movement plane, positive angles indicate flexion. In the frontal movement plane, positive angles indicate abduction. No significant differences between healthy and affected limb have been found.

Discrete joint analysis showed no significant differences between healthy and affected limb in any of the joints and movement planes. For detailed numerical results of the paired statistical tests, please refer to Table E3 in Appendix E. No significant differences in joint kinematics have been found between the healthy and affected limb.

180° change-of-direction
Due to unforeseen approach techniques of the CoD180, only three participants have been studied for this analysis. Consequently, the data was assumed to be non-normally distributed. Results of discrete joint analysis are shown in Figure 17.

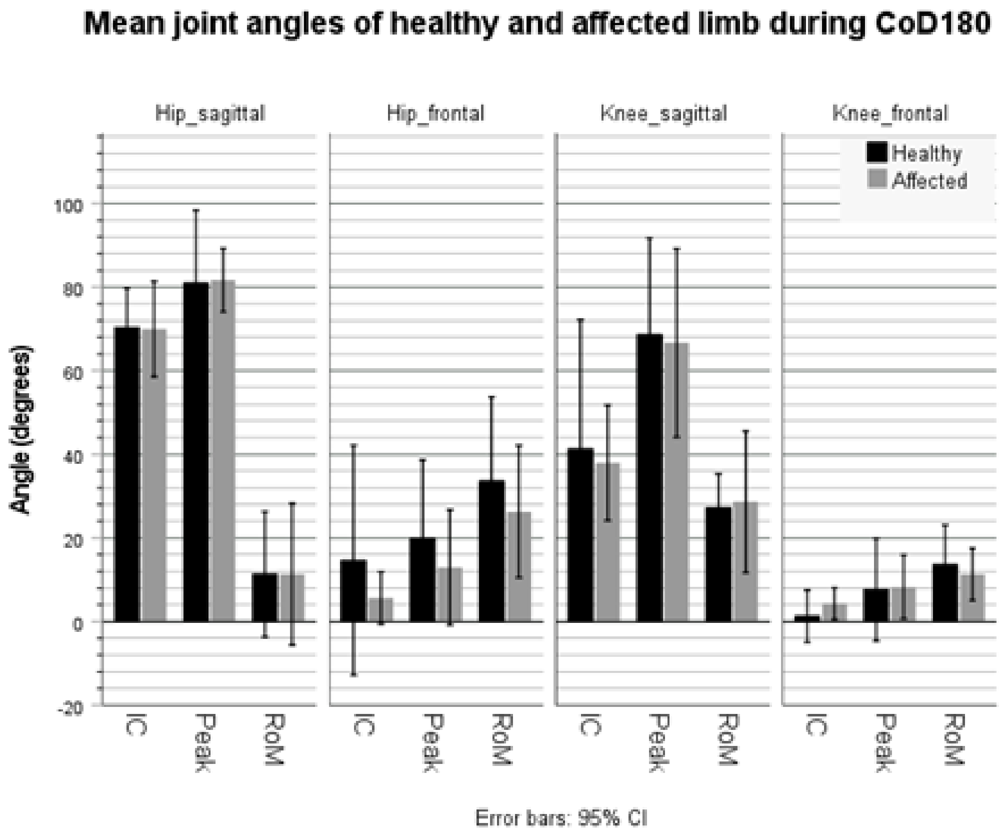


Figure 18: Results of discrete joint analysis. Results are presented as mean and standard deviations. In the sagittal movement plane, positive angles indicate flexion. In the frontal movement plane, positive angles indicate abduction. No significant differences between healthy and affected limb have been found.

Discrete joint analysis showed no significant differences between healthy and affected limb in any of the joints and movement planes. For detailed numerical results of the paired statistical tests, please refer to Table E4 in Appendix E. No significant differences in joint kinematics have been found between the healthy and affected limb.

Change-of-direction performance

Results of the Kolmogorov-Smirnov test of normality are shown in Table E2 in Appendix E. The Kolmogorov-Smirnov showed that all change-of-direction performance measures of the CoD90 were normally distributed. Results of the paired statistical tests are shown in Table 4.

Table 4: Results of paired statistical testing of change-of-direction performance measures

Performance measure	Healthy limb (mean ± SD)	Affected limb (mean ± SD)	p-value
90° change-of-direction			
Mediolateral foot placement distance (m)	0.47 ± 0.06	0.45 ± 0.05	0.563
Change-of-direction velocity (m/s)	2.24 ± 0.7	2.15 ± 0.5	0.468
Ground contact time (s)	0.29 ± 0.05	0.30 ± 0.03	0.543
Radius best-fit circle (m)	0.91 ± 0.3	1.15 ± 0.3	0.025
180° change-of-direction			
Mediolateral foot placement distance (m)	0.33 ± 0.09	0.27 ± 0.05	0.285
Change-of-direction velocity (m/s)	0.73 ± 0.29	1.17 ± 0.45	0.109
Distance ingoing-outgoing path (m)	0.63 ± 0.23	1.09 ± 0.29	0.109
Ground contact time (s)	0.25 ± 0.03	0.25 ± 0.03	0.655

* *Statistically significant*

90° change-of-direction
All change-of-direction performance measures were normally distributed. Results of the paired t-test are shown in Table 4. After adjustment of the significance level Bonferroni-Holm correction, no significant differences in change-of-direction performance measures were found between healthy and affected leg.

180° change-of-direction
Due to the low sample size, data was assumed to be non-normally distributed. Results of Wilcoxon's test are shown in Table 4. Wilcoxon's test showed no significant differences in change-of-direction performance measures between the healthy and affected limb.

Discussion

On-field movement analysis could provide valuable information about the movement quality of patients rehabilitating from ACL reconstruction. Despite its potential, assessment of on-field movement quality and change-of-direction performance is commonly absent. To address this gap, this study analyzed joint kinematics and change-of-direction performance in male soccer players after ACL reconstruction. However, several limitations should be considered.

First, the sample size of the study is limited. A small sample size increases the probability of Type II errors, leading to nonsignificant results. [31] Although inclusion and exclusion criteria were required to ensure patient safety, they also limited the number of eligible participants.

Second is that participants were initially not instructed on how to perform the change-of-direction maneuvers. As a result, some participants performed all CoD180 on the same limb, limiting comparison possibilities between the healthy and affected limb. Participants preferred performing the CoD180 on their dominant limb, regardless of the affected limb. Consequentially, a protocol change was implemented to ensure comparison of joint kinematics and change-of-direction performance measures between healthy and affected limb during CoD180. The CoD180 could only be analyzed for three participants, resulting in a very limited sample size.

Third is the comparison of joint kinematics of the affected limb with the healthy limb. ACL injury can lead to bilaterally altered movement patterns. [32] The absence of significant differences in joint kinematics between the healthy and affected leg might indicate movement quality is either fully restored or bilaterally impaired. Detection of decreased movement quality of the affected and healthy limb requires benchmark values from healthy participants, which demands extensive research on a large scale.

Fourth is that leg dominance was not accounted for in this study. Clemente et al. [33] reported faster change-of-direction performance on the dominant leg. In this study, four participants underwent ACL reconstruction on the non-dominant leg. When comparing results on participant level, three of these participants scored the highest differences in change-of-direction tightness between the healthy and affected leg. Therefore, change-of-direction tightness might be affected by leg dominance, suggesting a need for further investigation. For other change-of-direction performance measures, no other trends were found on participant level within this study population.

Fifth is the restriction to investigating preplanned movement only. As movement quality is affected by neurocognitive load, kinematic results of preplanned movement are not directly translatable to those resulting from unplanned movement. Adding neurocognitive load to the on-field test might increase differences in movement quality and change-of-direction performance between healthy and affected limb. [10, 32] However, this requires a more in-depth analysis of unplanned movement measured on-field.

Sixth is the poor height estimation of the inertial measurement units. The inertial measurement units showed physically implausible pelvis height, commonly initializing at random moments during a 'change-of-direction t-test' trial (Figure 16). The sensors showed decreased height of all body segments, sometimes decreasing below the floor level of calibration. Trouble with height estimation was not seen during the same maneuvers discussed in Part I of this report. In Part I of this research, movement was captured with the XSens LINK system. In Part II of this research, movement was captured with the XSens MTw Awinda system. Potentially, the improper height estimation was caused by the unstable mounting system of the XSens MTw Awinda. The velcro straps might have shifted or tilted the sensors in response to high-impact maneuvers. Consequently, the inertial measurement units detected a downward acceleration, leading to a drift in height estimation. As a result, both change-of-direction maneuvers and foot contact data had to be identified manually for all trials of all participants, making this a time-consuming procedure. For this test to be appropriate for daily practice, analysis should be primarily automated. A reconsideration of the use of the XSens MTw Awinda system for analysis of performance during the 'change-of-direction t-test' might be required for further investigations. Instead, using the XSens LINK system or markerless motion capture might provide opportunities for a more automated analysis process.

The ACL-RSI indicates psychological readiness to return to sport. [14] When assessing scores individually, a trend was found where patients reporting higher ACL-RSI scores underwent ACL reconstruction more recently. A potential explanation for this could be that participants who took longer to be cleared for on-field rehabilitation sessions encountered more setbacks during their rehabilitation. As a result, their psychological readiness to return to sport decreased. Participants with higher ACL-RSI scores displayed smaller differences in change-of-direction velocity between the healthy and affected side during the CoD90. Therefore, psychological readiness could potentially be a predictor of change-of-direction performance. For the other change-of-direction performance measures, no trends were found with ACL-RSI score.

Though not statistically significant, the healthy limb showed tighter change-of-direction maneuvers. During a change-of-direction maneuver, a participant must redirect the horizontal center of mass velocity toward the intended direction. Braking forces are required to decrease speed in the initial direction. [34] Consecutively, the direction of the ground reaction force needs to become more medially orientated. [35] Orientation of the ground reaction force can be facilitated by mediolateral foot placement distance, which is promoted by hip abduction. [24] However, in this research no significant differences in mediolateral foot placement distance and hip abduction have been found between the healthy and affected limb. Speculatively, patients spread the deceleration for directional changes on the affected limb over a longer period, to reduce breaking forces. Further investigation is required to analyze change-of-direction tightness and potential underlying mechanisms of this altered movement strategy. Deceleration strategies and change-of-direction tightness present compelling measures for further investigation of change-of-direction performance.

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General discussion

Literature about on-field kinematic assessment during change-of-direction maneuvers is limited. This thesis aimed to bridge the gap between in-lab and on-field kinematic measurements. Firstly, the effect of measurement surface on performance during the 'change-of-direction t-test' was analyzed. Statistically significant differences have been found among measurement surfaces in change-of-direction performance measures and joint kinematics in healthy soccer players. During the CoD90, ground contact time on turf and grass surface was lower than on the the tartan surface. Ankle transverse plane kinematics showed significant differences, where the ankle was more externally rotated on the tartan surface. During the CoD180, the horizontal velocity on the turf surface was significantly lower than grass and tartan surface. Hip sagittal plane, ankle sagittal plane, and ankle transverse plane were significantly different among measurement surfaces. Though the sample size was limited, these differences indicate that results from in-lab measurements are not directly translatable to results from on-field measurements. This highlights the importance of measuring in an ecologically valid environment.
Secondly, the joint kinematics and change-of-direction performance of soccer players rehabilitating from ACL reconstruction during the 'change-of-direction t-test' were analyzed for statistical differences between healthy and affected limb. No significant differences between healthy and affected leg were found. The lack of significant differences can be caused by low sample size, and either fully restored or bilaterally impaired movement quality. For the latter, benchmark values of healthy controls are required.
Healthy participants (Part I) and ACL patients (Part II) both performed the on-field 'change-of-direction t-test' on artificial turf. Therefore, the joint kinematics and change-of-direction performance of both populations can be compared. The differences between the healthy participants and the ACL patients were visually assessed without statistical testing. While hip range of motion is similar in size, hip angles at initial contact and peak flexion angles are roughly twenty degrees higher for the ACL patient population. When analyzing hip flexion angles of ACL patients on a participant scale, no trend is found between the discrete hip joint data in the sagittal movement plane and ACL-RSI score, the number of weeks post-surgery, or the amount of on-field rehabilitation sessions. Both populations are similar in body height, thus eliminating body height as a potential determinant for differences in hip flexion angles. Another explanation might be the modulation of the center of mass height before the directional change. Hip and knee flexion decreases center of mass height, which is considered an important factor in fast directional changes. [1] When changing direction in a lateral motion, the ground reaction force vector is directed from the center of pressure (foot) to the center of mass (pelvis). A lower center of mass directs the ground reaction force vector more laterally, allowing propulsive forces in the opposite direction. [1, 2] However, change-of-direction velocity was similar for both populations. Alternatively, disagreement of measurement equipment is the cause of the differences in hip flexion. Different inertial measurement unit systems have been used for the studies. Since other discrete joint data seem similar, this seems unlikely. As increased hip flexion at initial contact is a risk factor for sustaining ACL injuries [3], further investigation is required to explore the biomechanical factors influencing hip flexion angles in ACL patients. Besides that, these results highlight the importance of introducing reference values of healthy controls.

To conclude, measurement surface affects ankle joint kinematics and change-of-direction performance of healthy soccer players. This highlights the importance of measuring in an ecologically valid environment. No significant differences between healthy and affected limb have been found in joint kinematics and change-of-direction performance in soccer players after ACL reconstruction. Both studies conducted in this thesis served an explorative purpose. Further research is required to overcome sample size limitations. Perceived grip, change-of-direction tightness and deceleration present compelling measures for further investigation of change-of-direction performance. Furthermore, adding a stimulus to the set-up would increase ecological validity.

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Appendix A: Discrete joint analysis for CoD90

Table A1: Results of Kolmogorov-Smirnov test and Mauchly's Test of Sphericity

Movement plane	Joint	Discrete point	Kolmogorov-Smirnov Tartan (p-value)	Kolmogorov-Smirnov Turf (p-value)	Kolmogorov-Smirnov Grass (p-value)	Mauchly's test (p-value)
Sagittal	Hip	IC(°)	0.200	0.200	0.200	0.977
		Peak(°)	0.200	0.200	0.169	0.889
		Range of Motion(°)	0.200	0.200	0.200	0.951
	Knee	IC(°)	0.200	0.200	0.200	0.120
		Peak(°)	0.200	0.200	0.200	0.078
		Range of Motion(°)	0.200	0.093	0.200	0.589
	Ankle	IC(°)	0.200	0.200	0.100	0.738
		Peak(°)	0.200	0.200	0.200	0.668
		Range of Motion(°)	0.200	0.200	0.200	0.295
Frontal	Hip	IC(°)	0.112	0.007*	0.200	-
		Peak(°)	0.200	0.200	0.200	0.249
		Range of Motion(°)	0.150	0.200	0.200	0.525
	Knee	IC(°)	0.200	0.200	0.200	0.162
		Peak(°)	0.200	0.200	0.200	0.737
		Range of Motion(°)	0.200	0.136	0.200	0.433
	Ankle	IC(°)	0.200	0.200	0.200	0.051
		Peak(°)	0.200	0.200	0.081	0.009 ^{M}
		Range of Motion(°)	0.200	0.157	0.200	0.926
Transverse	Hip	IC(°)	0.200	0.053	0.200	0.157
		Peak(°)	0.200	0.011*	0.064	-
		Range of Motion(°)	0.200	0.200	0.088	0.128
	Knee	IC(°)	0.035*	0.200	0.200	-
		Peak(°)	0.200	0.200	0.120	0.982
		Range of Motion(°)	0.200	0.200	0.200	0.471
	Ankle	IC(°)	0.200	0.200	0.200	0.099
		Peak(°)	0.200	0.200	0.200	0.973
		Range of Motion(°)	0.200	0.004*	0.200	-

Table A2: Results of ANOVA Repeated Measures of discrete joint kinematics during CoD90

Movement plane	Joint	Discrete point	Tartan (mean ± SD)	Turf (mean ± SD)	Grass (mean ± SD)	p-value
Sagittal	Hip	IC(°)	52.7 ± 9.1	49.0 ± 10.5	47.9 ± 8.8	0.040
		Peak(°)	65.1 ± 11.4	60.8 ± 13.2	59.3 ± 11.5	0.034
		Range of motion(°)	12.4 ± 5.5	11.8 ± 5.6	11.4 ± 4.1	0.567
	Knee	IC(°)	32.5 ± 4.8	32.4 ± 5.3	33.3 ± 5.1	0.799
		Peak(°)	71.6 ± 5.0	72.4 ± 7.7	69.9 ± 4.6	0.224
		Range of motion(°)	39.1 ± 4.5	40.0 ± 6.8	36.6 ± 5.9	0.078
	Ankle	IC(°)	-4.6 ± 5.1	-6.1 ± 7.4	-4.8 ± 7.0	0.566
		Peak(°)	24.7 ± 6.9	23.1 ± 7.8	23.7 ± 7.4	0.646
		Range of motion(°)	29.3 ± 6.2	29.2 ± 3.9	28.4 ± 4.5	0.736
Frontal	Hip	IC(°)	-2.25 ± 5.8	1.6 ± 6.1	-2.0 ± 5.5	0.627^{F}
		Peak(°)	3.5 ± 4.7	3.8 ± 4.3	2.8 ± 4.7	0.492
		Range of motion(°)	12.8 ± 2.6	13.2 ± 3.0	12.5 ± 2.4	0.451
	Knee	IC(°)	4.7 ± 4.0	5.4 ± 3.9	5.8 ± 3.5	0.193
		Peak(°)	9.6 ± 2.1	9.9 ± 1.6	9.5 ± 2.0	0.563
		Range of motion(°)	12.7 ± 2.9	12.6 ± 2.0	11.9 ± 2.2	0.381
	Ankle	IC(°)	1.6 ± 6.7	-0.1 ± 8.6	-1.0 ± 6.7	0.202
		Peak(°)	15.4 ± 4.2	15.0 ± 6.9	11.1 ± 5.8	0.209^{G}
		Range of motion(°)	20.2 ± 3.7	20.0 ± 2.8	17.1 ± 3.4	0.007*
Transverse	Hip	IC(°)	16.0 ± 5.7	16.0 ± 5.2	16.5 ± 5.7	0.870
		Peak(°)	23.0 ± 6.9	23.2 ± 7.0	22.9 ± 6.7	0.449^{F}
		Range of motion(°)	12.5 ± 3.0	11.9 ± 3.5	10.9 ± 3.0	0.088
	Knee	IC(°)	3.9 ± 2.8	4.0 ± 2.8	3.8 ± 2.2	0.627^{F}
		Peak(°)	8.4 ± 1.7	8.3 ± 1.9	7.8 ± 2.0	0.159
		Range of motion(°)	10.3 ± 1.8	10.1 ± 2.1	9.4 ± 2.2	0.073

Continued on next page

Table A2 – continued from previous page

Movement plane	Joint	Discrete point	Tartan (mean ± SD)	Turf (mean ± SD)	Grass (mean ± SD)	p-value
	Ankle	IC(°)	-11.2 ± 5.3	-5.9 ± 7.7	-5.4 ± 7.2	0.002*
		Peak(°)	0.2 ± 4.7	3.1 ± 5.5	2.8 ± 4.3	0.135
		Range of motion(°)	23.1 ± 4.0	21.4 ± 4.6	19.7 ± 4.2	0.127

** statistically significant ^{F} Friedman's test ^{G} Greenhouse-Geisser*

Appendix B: Continuous joint analysis for CoD90

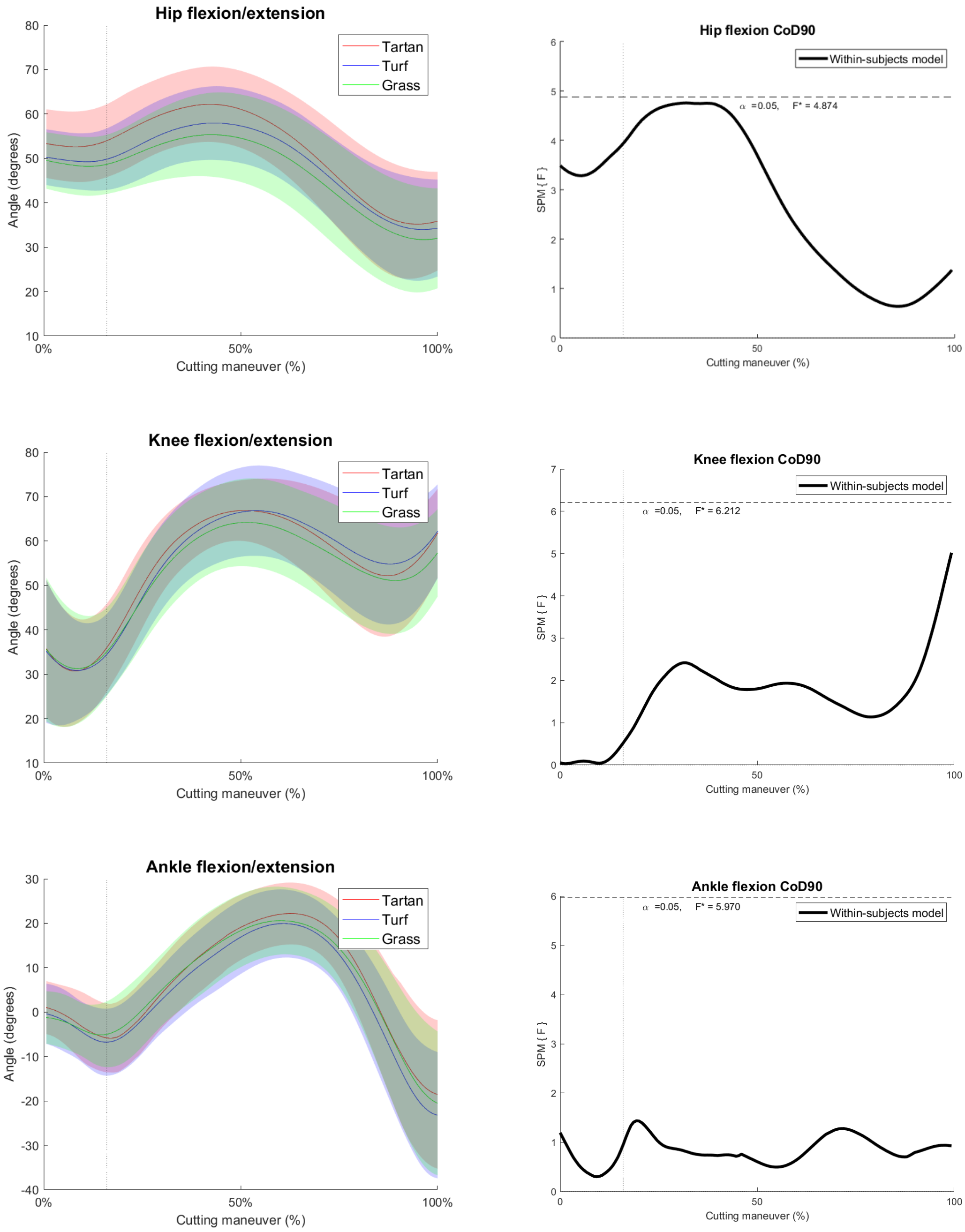

Figure C1: Results of continuous joint analysis for hip, knee, and ankle joint in the sagittal movement plane. In the left column, the bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistically significant differences have been found among measurement surfaces. In the right column, mean and standard deviation of joint movements are shown for tartan (red), artificial turf (blue), and natural grass (green).

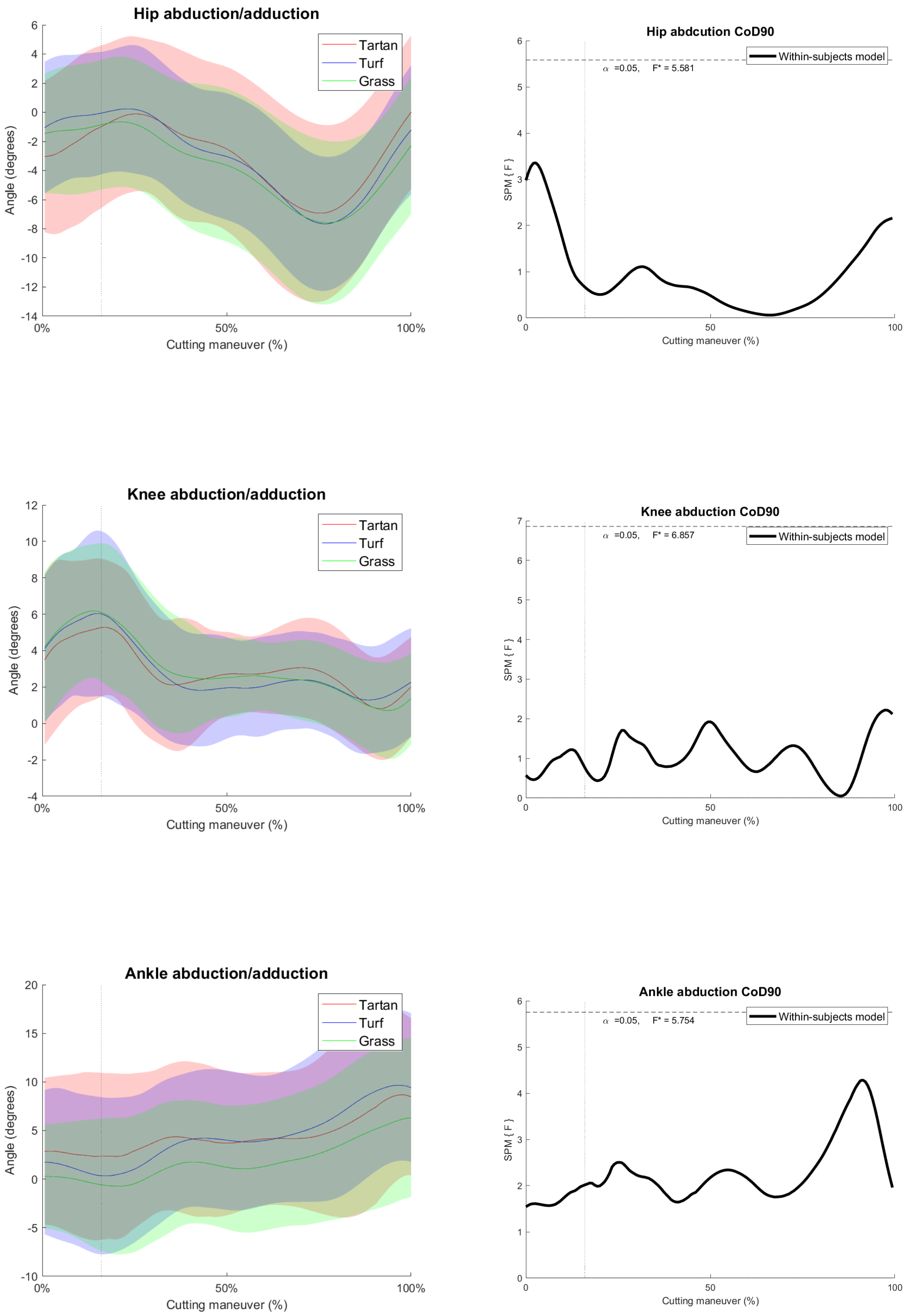

Figure C2: Results of continuous joint analysis for hip, knee, and ankle joint in the frontal movement plane. In the left column, the bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistically significant differences have been found among measurement surfaces. In the right column, mean and standard deviation of joint movements are shown for tartan (red), artificial turf (blue), and natural grass (green).

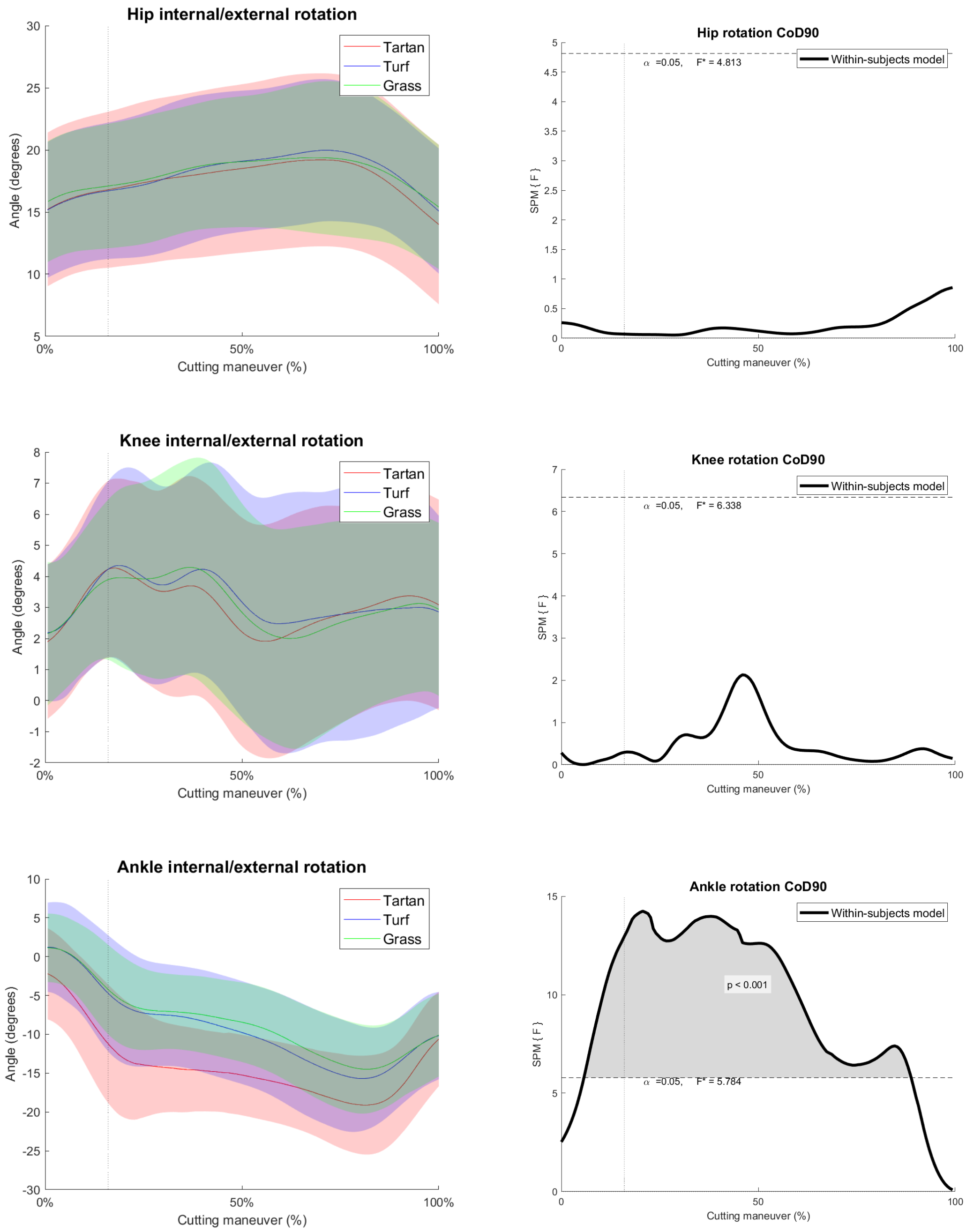

Figure C3: Results of continuous joint analysis for hip, knee, and ankle joint in the transverse movement plane. In the left column, the bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistically significant differences have been found among measurement surfaces. In the right column, mean and standard deviation of joint movements are shown for tartan (red), artificial turf (blue), and natural grass (green).

Appendix C: Discrete joint analysis for CoD180

Table C1: Results of the Kolmogorov-Smirnov test and Mauchly's Test of Sphericity

Movement plane	Joint	Discrete point	Kolmogorov-Smirnov Tartan (p-value)	Kolmogorov-Smirnov Turf (p-value)	Kolmogorov-Smirnov Grass (p-value)	Mauchly's test (p-value)
Sagittal	Hip	IC(°)	0.200	0.200	0.200	0.983
		Peak(°)	0.200	0.063	0.200	0.691
		Range of Motion(°)	<0.001*	0.023	0.199	-
	Knee	IC(°)	0.200	0.200	0.155	0.640
		Peak(°)	0.200	0.175	0.060	0.948
		Range of Motion(°)	0.200	0.025*	0.200	-
	Ankle	IC(°)	0.200	0.200	0.200	0.751
		Peak(°)	0.200	0.200	0.200	0.601
		Range of Motion(°)	0.200	0.052	0.200	0.552
Frontal	Hip	IC(°)	0.079	0.026*	0.075	-
		Peak(°)	0.200	0.065	0.200	0.367
		Range of Motion(°)	0.126	0.200	0.200	0.018^{M}
	Knee	IC(°)	0.200	0.009*	0.176	0.918
		Peak(°)	0.200	0.136	0.200	0.287
		Range of Motion(°)	0.200	0.104	0.200	0.957
	Ankle	IC(°)	0.200	0.200	0.200	0.195
		Peak(°)	0.200	0.200	0.200	0.904
		Range of Motion(°)	0.200	0.078	0.200	0.275
Transverse	Hip	IC(°)	0.028*	0.200	0.200	-
		Peak(°)	0.046*	0.200	0.040*	-
		Range of Motion(°)	0.017*	0.200	<0.001*	-
	Knee	IC(°)	0.200	0.200	0.200	0.622
		Peak(°)	0.200	0.168	0.124	0.663
		Range of Motion(°)	0.200	0.038*	0.065	0.109
	Ankle	IC(°)	0.181	0.200	0.200	0.772
		Peak(°)	0.083	0.200	0.200	0.991
		Range of Motion(°)	0.200	0.200	0.200	0.719

**: Absence normal distribution*
^{M}*: Variances of the differences are not equal*
-: Absence normal distributions, Mauchly's test not performed

Table C2: Results of ANOVA Repeated Measures of discrete joint kinematics during CoD180

Movement plane	Joint	Discrete point	Tartan (mean ± SD)	Artificial turf (mean ± SD)	Natural grass (mean ± SD)	p-value
Sagittal	Hip	IC(°)	47.8 ± 6.4	43.2 ± 10.2	43.0 ± 9.0	0.033
		Peak(°)	56.6 ± 9.5	53.3 ± 10.2	53.5 ± 12.1	0.175
		Range of motion(°)	8.8 ± 5.8	10.1 ± 5.3	10.5 ± 5.3	0.766 ^{F}
	Knee	IC(°)	34.8 ± 6.5	38.8 ± 9.8	37.6 ± 9.8	0.107
		Peak(°)	70.4 ± 6.4	75.0 ± 9.2	72.5 ± 7.7	0.210
		Range of motion(°)	35.6 ± 11.3	36.1 ± 8.8	34.9 ± 9.8	0.766 ^{F}
	Ankle	IC(°)	-0.1 ± 10.1	2.8 ± 8.2	2.0 ± 7.7	0.164
		Peak(°)	27.0 ± 8.2	22.8 ± 7.2	22.6 ± 8.9	0.016*
		Range of motion(°)	27.1 ± 7.5	20.0 ± 6.2	20.6 ± 7.6	<0.001*
Frontal	Hip	IC(°)	-5.1 ± 5.8	-5.5 ± 6.6	-4.5 ± 4.7	0.420 ^{F}
		Peak(°)	-0.8 ± 5.2	-0.5 ± 5.8	0.1 ± 4.4	0.678
		Range of motion(°)	12.0 ± 2.5	12.8 ± 1.9	13.0 ± 2.3	0.260 ^{G}
	Knee	IC(°)	6.2 ± 3.7	4.3 ± 4.2	5.4 ± 3.2	0.086
		Peak(°)	10.7 ± 2.1	9.8 ± 1.8	9.8 ± 2.4	0.204
		Range of motion(°)	13.6 ± 2.2	13.7 ± 3.6	13.0 ± 3.0	0.485
	Ankle	IC(°)	2.1 ± 6.7	1.2 ± 9.6	0.3 ± 6.1	0.583
		Peak(°)	14.7 ± 7.5	15.2 ± 9.2	13.3 ± 6.4	0.633
		Range of motion(°)	19.9 ± 3.9	21.1 ± 5.8	18.6 ± 4.6	0.196
Transverse	Hip	IC(°)	12.4 ± 3.6	12.4 ± 5.3	13.8 ± 5.3	0.549 ^{F}
		Peak(°)	13.4 ± 5.1	13.5 ± 5.6	15.4 ± 6.4	0.155 ^{F}
		Range of motion(°)	7.9 ± 2.4	7.7 ± 2.9	8.8 ± 3.2	0.627 ^{F}
	Knee	IC(°)	6.6 ± 3.6	6.3 ± 4.1	7.1 ± 4.1	0.699
		Peak(°)	7.3 ± 2.8	6.5 ± 2.3	6.8 ± 1.9	0.268
		Range of motion(°)	10.3 ± 2.4	10.7 ± 3.0	10.4 ± 2.9	0.769
	Ankle	IC(°)	-14.3 ± 4.5	-9.9 ± 6.3	-8.7 ± 5.8	<0.001*
		Peak(°)	-2.6 ± 3.7	0.2 ± 4.5	0.0 ± 5.0	0.095
		Range of motion(°)	21.9 ± 3.9	19.8 ± 4.6	17.8 ± 4.1	0.002*

** statistically significant ^{G} Greenhouse-Geisser ^{F} Friedman's test*

Appendix D: Continuous joint analysis for CoD180

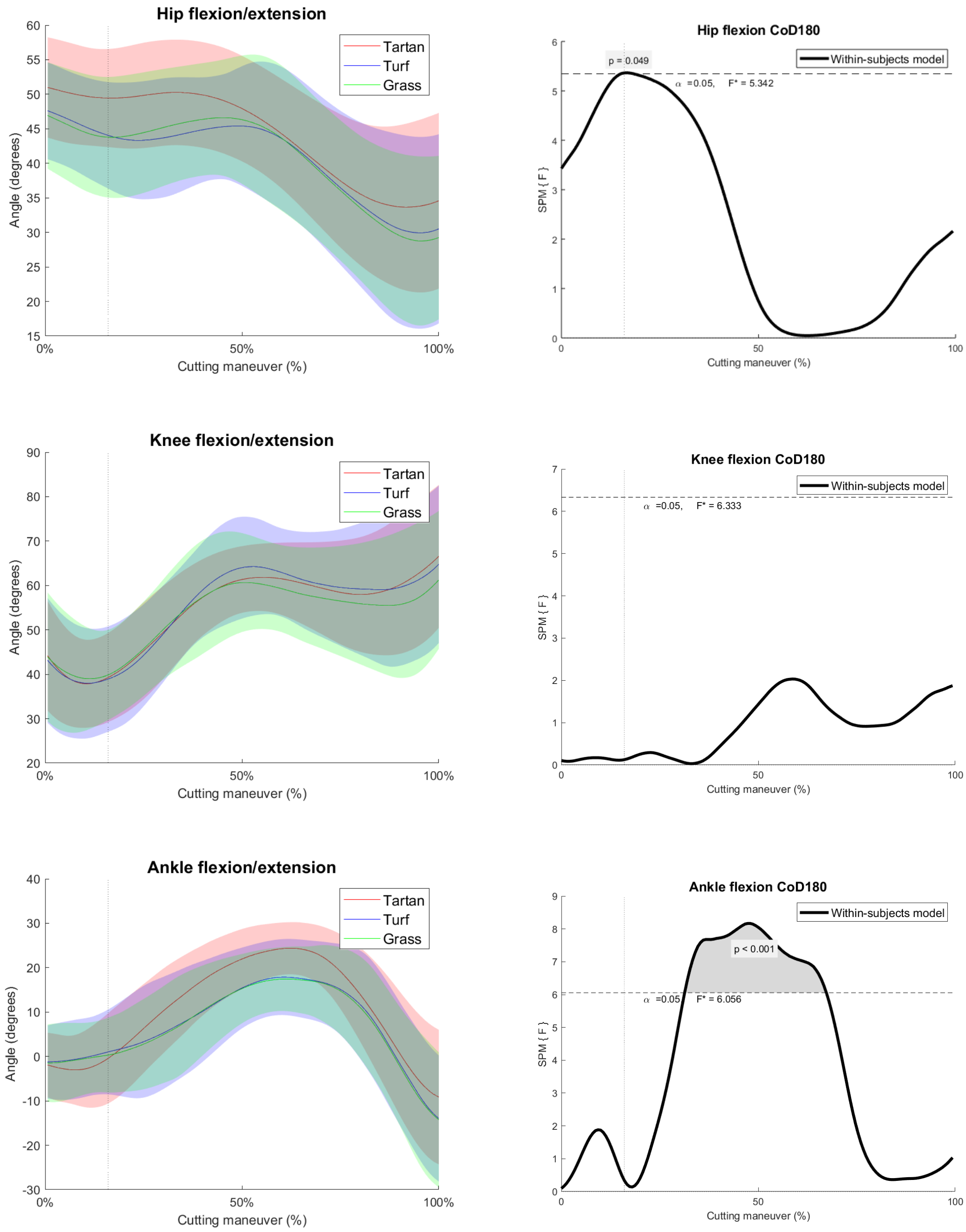

Figure D1: Results of continuous joint analysis of 180° change-of-direction maneuvers for hip, knee, and ankle joint in the sagittal movement plane. In the left column, the bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistically significant differences have been found among measurement surfaces. In the right column, mean and standard deviation of joint movements are shown for tartan (red), artificial turf (blue), and natural grass (green).

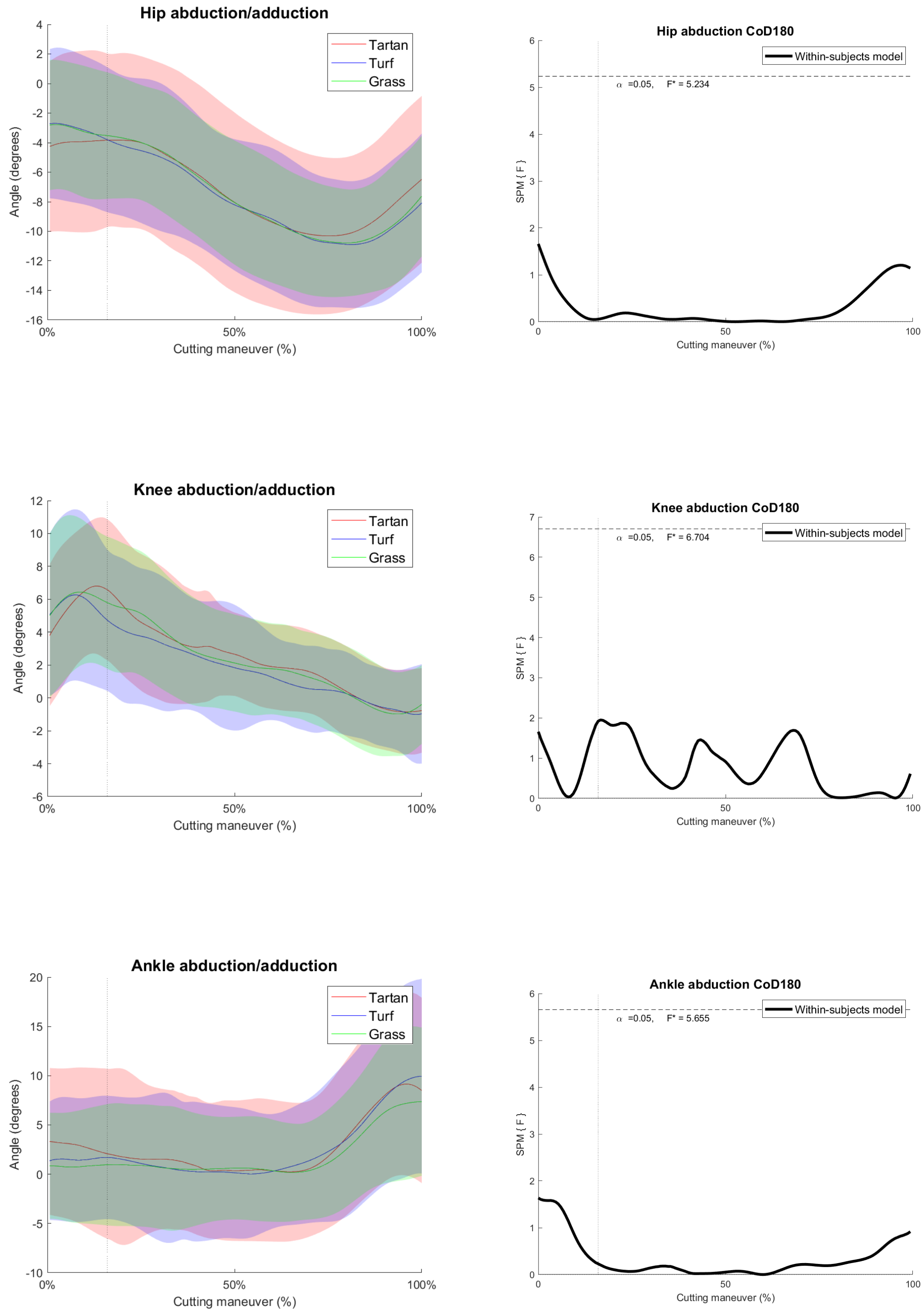

Figure D2: Results of continuous joint analysis of 180° change-of-direction maneuvers for hip, knee, and ankle joint in the frontal movement plane. In the left column, the bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistically significant differences have been found among measurement surfaces. In the right column, mean and standard deviation of joint movements are shown for tartan (red), artificial turf (blue), and natural grass (green).

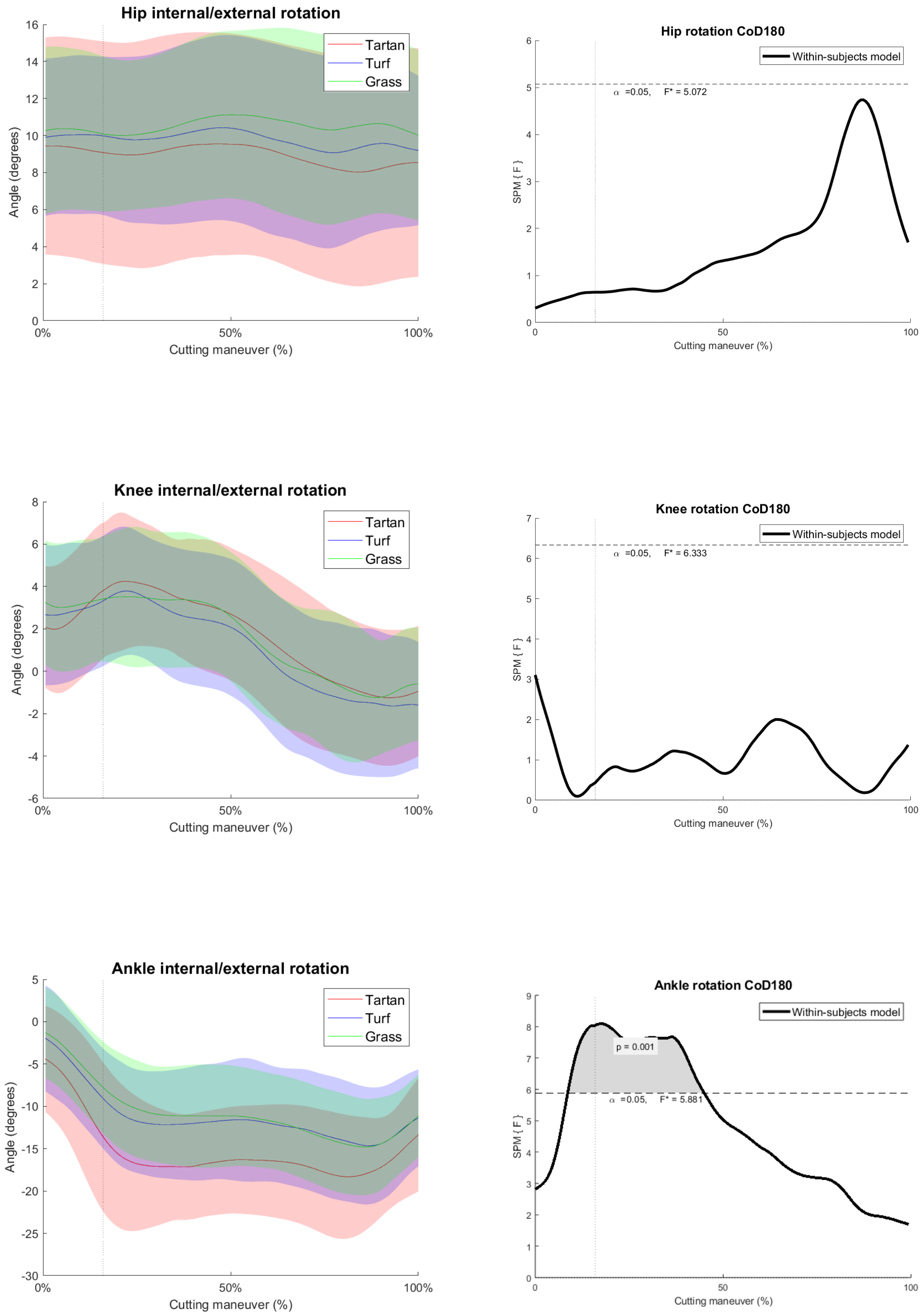

Figure D3: Results of continuous joint analysis of 180° change-of-direction maneuvers for hip, knee, and ankle joint in the transverse movement plane. In the left column, the bold line shows the time series of F-values. The dashed horizontal line is the critical value threshold ($\alpha = 5\%$). The grey area under the curve shows the regions of the movement curve for which statistically significant differences have been found among measurement surfaces. In the right column, mean and standard deviation of joint movements are shown for tartan (red), artificial turf (blue), and natural grass (green).

Appendix E: Discrete joint analysis Part II

Results of the Kolmogorov-Smirnov test of discrete joint data for the 90° change-of-direction. Data was considered normally distributed if p>0.05.

Table E1: Results of paired statistical tests for CoD90

Movement plane	Joint	Discrete point	p-value healthy	p-value affected
Sagittal	Hip	IC(°)	0.200	0.200
		Peak(°)	0.200	0.196
		Range of motion(°)	0.165	0.150
	Knee	IC(°)	0.200	0.200
		Peak(°)	0.200	0.200
		Range of motion(°)	0.200	0.200
Frontal	Hip	IC(°)	0.140	0.200
		Peak(°)	0.128	0.200
		Range of motion(°)	0.200	0.200
	Knee	IC(°)	0.200	0.200
		Peak(°)	0.001*	0.200
		Range of motion(°)	0.200	0.200

Results of the Kolmogorov-Smirnov test of change-of-direction performance measures for the 90° change-of-direction. Data was considered normally distributed if p>0.05.

Table E2: Results of paired statistical tests for CoD90

Performance measure	p-value healthy	p-value affected
Mediolateral foot placement distance	0.200	0.200
Change-of-direciton velocity	0.138	0.152
Ground contact time	0.200	0.200
Change-of-direction tightness	0.200	0.200

$* : not normally distributed$

Results of paired statistical tests for discrete joint kinematic data of the 90° change-of-direction. Differences between healthy and affected limb were considered statistically significant if $p < 0.05$. Normally distributed variables were tested with the paired t-test. Wilcoxon's test was used for variables that were not normally distributed.

Table E3: Results of paired statistical tests for CoD90

Movement plane	Joint	Discrete point	Healthy limb (mean ± SD)	Affected limb (mean ± SD)	p-value
Sagittal	Hip	IC(°)	74 ± 4	71 ± 4	0.253
		Peak(°)	89 ± 3	89 ± 6	0.467
		Range of motion(°)	11 ± 2	18 ± 4	0.194
	Knee	IC(°)	36 ± 2	33 ± 2	0.247
		Peak(°)	70 ± 3	74 ± 3	0.452
		Range of motion(°)	34 ± 3	40 ± 4	0.285
Frontal	Hip	IC(°)	9 ± 5	9 ± 3	0.974
		Peak(°)	14 ± 5	17 ± 4	0.681
		Range of motion(°)	23 ± 2	26 ± 3	0.301
	Knee	IC(°)	5 ± 2	5 ± 2	0.156^W
		Peak(°)	9 ± 1	14 ± 3	0.167
		Range of motion(°)	13 ± 2	16 ± 3	0.409

^{W}*: p-values calculated with Wilcoxon's test. All other p-values are calculated with paired t-test*

Results Wilcoxon's test for discrete joint kinematic data of the 180° change-of-direction. Differences between healthy and affected limb were considered statistically significant if $p < 0.05$. Normally distributed variables were tested with the paired t-test. Wilcoxon's test was used for variables that were not normally distributed.

Table E4: Results of Wilcoxon's test for CoD180

Movement plane	Joint	Discrete point	Healthy limb (mean ± SD)	Affected limb (mean ± SD)	p-value
Sagittal	Hip	IC(°)	70 ± 2	70 ± 3	1.00^{W}
		Peak(°)	81 ± 4	82 ± 2	0.593^{W}
		Range of motion(°)	11 ± 3	11 ± 4	1.00^{W}
	Knee	IC(°)	41 ± 7	38 ± 3	0.414^{W}
		Peak(°)	69 ± 5	67 ± 5	1.00^{W}
		Range of motion(°)	27 ± 2	29 ± 4	0.655^{W}
Frontal	Hip	IC(°)	15 ± 7	6 ± 1	0.285^{W}
		Peak(°)	20 ± 4	13 ± 3	0.285^{W}
		Range of motion(°)	34 ± 5	26 ± 4	0.285^{W}
	Knee	IC(°)	1 ± 1	4 ± 1	0.180^{W}
		Peak(°)	8 ± 3	8 ± 2	0.655^{W}
		Range of motion(°)	14 ± 2	11 ± 1	0.109^{W}

^{W}: *p-values calculated with Wilcoxon's test. All other p-values are calculated with paired t-test*