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Research Article / Araştırma Makalesi

Recreational male athletes' single leg forward hop and crossover triple hop test kinetics, kinematics, peak frequency and magnitude alterations

Rekreasyonel erkek sporcularda tek bacak ileri sekme ve çapraz üçlü sekme testlerinde kinetik, kinematik, zirve frekansı ve şiddet değişimleri

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ABSTRACT

Objective: Single-leg forward and crossover triple hop tests are predictors of recovery and return-to-sports after lower extremity injury and treatment. The purpose of the study is to assess the kinematic and kinetic feasibility and repeatability of a motion analysis base for these hop tests in recreational male athletes.

Methods: Normal ranges of single- and crossover triple hop tests kinetics, kinematics, peak frequencies and magnitude alterations in spectral distributions were evaluated in 11 recreational male athletes. Ground reaction forces were measured using a force plate. A motion capture system was used to record peak knee flexion-extension angles. Peak frequency and magnitude characteristics in spectral distributions were calculated from these measurements.

Results: Ground reaction force normalized to body weight at landing was 2.9±0.1 (N/kg⋆10) in both legs during repetitions. Average flight over total time was 0.49±0.03 and 0.38±0.01 (s/s) for single and crossover triple hop tests, respectively. Flight, preparatory and total jump times were 0.301±0.020, 0.331±0.033 and 0.641±0.038 s for single, and 0.261±0.014, 0.453±0.024 and 0.701±0.046 s for crossover tests. Knee angle variations except for peak flexion angles were similar in both extremities. Main frequency spectral characteristic was about 2-4 Hz. First and second peak frequencies for the left and right leg were 3.19±0.17 and 7.16±0.17, and 3.15±0.16 and 7.18±0.19 Hz, respectively. Hop tests presented similar flight times during repetitions. This was however different during crossover jumps tests: flight times were shorter while preparatory times were longer. First characteristic frequency and magnitude were common in two tests.

Conclusions: Peak flexion and extension angles and second characteristic frequency in single tests were specific to each participant. Hop tests are responsive to different performance metrics and are repeatable and feasible, so these tests can be used to create a comparative database for athletes.

Keywords: *Sport biomechanics, knee injury, return to sports, joint kinematics, ground reaction force, injury prevention*

ÖZ

Amaç: Tek bacakla ileri ve çapraz üçlü sekme testleri, alt ekstremite yaralanması ve tedavisi sonrası iyileşme ve spora dönüşün öngörücüleridir. Bu çalışmanın amacı, rekreasyonel erkek sporcularda hareket analizinin kinematik ve kinetik değerlendirmesinin bu sekme testlerindeki uygulanabilirlik ve tekrarlanabilirliğini değerlendirmektir.

Yöntem: On bir erkek rekreasyonel sporcunun tekli ve çapraz üçlü sıçrama testleri sırasında alt ekstremite kinetiği, kinematiği, tepe frekansları ve spektral dağılımlardaki büyüklük değişikliklerinin normal aralıkları değerlendirildi. Yer reaksiyon kuvvetleri bir kuvvet levhası kullanılarak ölçüldü. Zirve diz fleksiyon-ekstansiyon açılarını kaydetmek için bir hareket yakalama sistemi kullanıldı. Spektral dağılımlardaki zirve frekansı ve şiddeti bu ölçümlerden yararlanılarak hesaplandı.

Bulgular: Tekrarlar sırasında inişteki vücut ağırlığına göre normalize edilmiş yer tepki kuvveti, her iki bacakta 2.9±0.1 (N/kg⋆10) idi. Tekli ve çapraz üçlü sıçrama testi için uçuş süresinin toplam hareket süresine oranının ortalaması, sırasıyla 0.49±0.03 ve 0.38±0.01 (s/s) idi. Uçuş, hazırlık ve toplam sıçrama süreleri sırasıyla tekli test için 0.301±0.020, 0.331±0.033 ve 0.641±0.038 s; çapraz test için 0.261±0.014, 0.453±0.024 ve 0.701±0.046 s idi. Zirve fleksiyon açısı hariç diz açısındaki diğer değişkenler her iki ekstremitede benzerdi. Hareketin ana frekansı yaklaşık 2-4 Hz idi. Sol ve sağ bacakta birinci ve ikinci zirve frekansları sırasıyla 3.19±0.17 ve 7.16±0.17; 3.15±0.16 ve 7.18±0.19 Hz idi. Sıçrama testleri, tekrarlar sırasında benzer uçuş süreleri gösterdi. Ancak bu durum çapraz testlerdeki sıçramalar sırasında farklıydı: uçuş süreleri daha kısayken, hazırlık süreleri daha uzundu. Frekans ve şiddetin karakteristik ilk zirvesi iki testte de ortaktı.

Sonuç: Tekli testlerdeki zirve fleksiyon ve ekstansiyon açıları ve ikincil karakteristik frekans, her katılımcı için farklıydı. Farklı performans metriklerine duyarlı olan sıçrama testleri tekrarlanabilir olup, sporcularda karşılaştırmalı bir veri tabanı oluşturmak için kullanılabilir.

Anahtar Sözcükler: *Spor biyomekaniği, diz yaralanması, spora dönüş, eklem kinematiği, yer tepki kuvveti, yaralanmadan korunma*

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INTRODUCTION

Return to sport (RTS) decision after lower extremity injury, treatment, and rehabilitation including anterior cruciate ligament reconstruction (ACLR) mostly depends on skeletal muscle strength and function measurements, including single and triple hop for distance tests (1). Validity and repeatability of these tests are frequently questioned (2,3), although they reduce the risk of re-injury. Limb symmetry index (LSI) ratio (injured leg/healthy leg × 100) may predict opposite extremity injury rates, which can be up to 50% in case of early RTS, or insufficient treatment and rehabilitation (4). Hop tests after ACLR are associated with RTS, but fail to identify the second injury risk (5,6). A recent study (7) focused on the importance of quantification of functional tests, where single leg forward hop tests (SFHT) were used to evaluate biomechanical performance(8).

Kinetic and kinematics of the SFHT and/or crossover triple hop tests (COHT) were however not investigated in time and frequency domain. Repeatability of functional tests is important to compare the results of athletes under normal and pathological conditions. We examined whether the repeated vertical ground reaction force (vGRF) normalized to body weight would be similar in both legs during SFHT and COHT in recreational male athletes. We further examined whether repeated flight and preparatory times, peak knee flexion-extension angles would be similar in both legs and in jumps during SFHT and COHT in the same group. We finally examined whether the first and the second peak frequency, and the magnitude characteristics in spectral distributions were similar in both legs during SFHT and COHT in these athletes.

Table 1. Participants' characteristics

Parameter	Average ± SD	(min - max)
Age (yrs)	28.1±2.1	(25-31)
Height (cm)	181.8±4.8	(170-187)
Body weight(kg)	81.5±8.1	(64-91)
BMI (kg/m²)	24.6±1.5	(22.1-27.7)
Leg length(cm)	88.2±3.7	(83-95)

The objective of this study was aimed to provide valuable insights into diverse metrics that can be utilized in the movement analysis of SFHT and COHT in recreational male athletes. Repeated vGRF normalized to body weight after landing on a force plate following the final third jump was compared between legs, recorded as the kinetic data using a motion analysis system. Repeated flight and preparatory times, peak knee flexion and extension angles provided the kinematic data. The first and the second peak frequency and magnitude characteristics in spectral distributions were evaluated through fast Fourier transformation (FFT) for knee flexion and extension angles.

MATERIAL and METHODS

Participants

Participants (Table 1) were informed on the aims and potential risks of the study, and written consent was obtained. All procedures were in compliance with the Declaration of Helsinki for human studies. Hacettepe University Non-Interventional Clinical Researches Ethics Board approved (23.02.2021-GO20/662) the study. Being a male recreational athlete with no history of previous ACL injury, repair, and/or reconstruction were our inclusion criteria. Participants were excluded if they reported acute lower extremity pain or injury that would affect jumping and landing performance, history of hip, ankle, and/or knee ligament injury experienced during the last six months, any lower extremity surgery, or any musculoskeletal/neurological condition that would limit the performance of the given tasks. Participants had participated in training or matches at least three days/wk for at least eight years. There were two basketball players, two soccer players, two runners, and five other participants who participated in fitness and yoga training. Leg length was measured with the tape measure method (9) between the anterior superior iliac spine (ASIS) and medial malleolus, to be used to normalize jumping distance between participants.

Experimental Design

We designed a cross-sectional non-interventional cohort study in eleven 18-35-year-old (average 28.1±2.1 years) male recreational athletes. Participants were asked to stand still in a quiet stance for about five seconds at the center of the force plate before each test for the proper construction of the rigid bodies after calibration. Independent variables were six repetitions (trials 1 to 6) of SFHT and COHT with both legs landing on the force plate after the third final jump. Take-off from the force plate after stabilization was further recorded (jump 4). Dependent variables were joint angle variations (KneeAngVar), peak flexion (PeakFlex), and extension (PeakExt) angle variation, and the ratio of flight over total jump time (FoT). The kinetic variable was the vGRF normalized to body weight (FPnorm) at landing. Frequencies (PeakFreq f1 and f2) and magnitudes (PeakMag f1 and f2) of the jumps at each trial were further calculated from the kinematic data.

Methodology

Kinematic and kinetic data were measured by a motion analysis system (PhaseSpace Impulse X2, PhaseSpace Inc., San Leandro, California, USA) and a custom-made 120x120 cm force plate (Bertec Inc., Columbus, Ohio, USA), respectively. The motion analysis system consisted of eight PhaseSpace cameras, LED sets, a server computer (Intel Pentium IV 3.0 GHz, 512 Mb RAM, graphics accelerator card Slackware 10.1, Linux Kernel v.2.6.15), a PhaseSpace hub, and the PhaseSpace server software. Kinematic and kinetic GRF data were sampled at 480 and 100 Hz, respectively (Figure 1). The motion analysis system and the force plate were synchronized during data collection and driven by a custom Matlab (The Mathworks©, Natick, USA) code. A PCI-6221 NI DAQ card (National Instruments©, Austin, USA) was used.

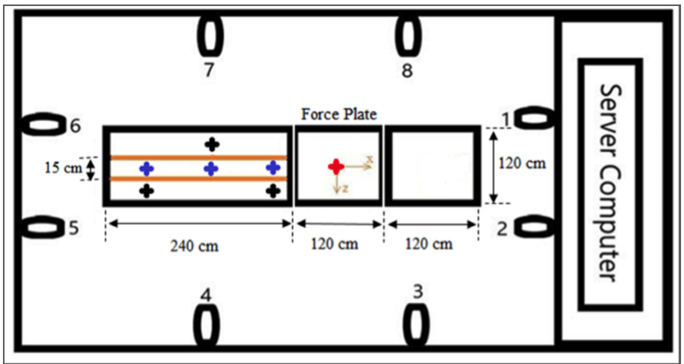

Figure 1. Layout of the motion capture setting (top view). Blue marks stand for SFHT for each foot, black marks stand for COHT for the left foot, red mark is the landing spot on the force plate for both tests.

Position and orientation data were obtained from LED sets, each containing four LEDs, which were fixed to body segments to construct rigid bodies (Figure 2). The body segments consisted of foot, shank, thigh, and trunk. Distance between each LED in each set is assumed to remain constant during the measurements. Relative orientation between two rigid bodies formed the joint angle. Knee joint motion was obtained by subtracting the orientation of the lower leg from that of the upper leg.

Time domain analysis: The presented data was divided into five segments (Figure 3). The first three segments were the recursive three jumps. The preparatory (P1) and the flight phases (F1) at each jump are presented. The ratio of F1 to the total jump time (P1+F1) was then defined as FoT. The participant was informed to come to rest at the possible shortest period of time after landing on the force plate. The fourth segment (S4) reflected the participants' stabilization and damping behavior. The fifth segment represented the take-off period performed after a short quiet stance epoch.

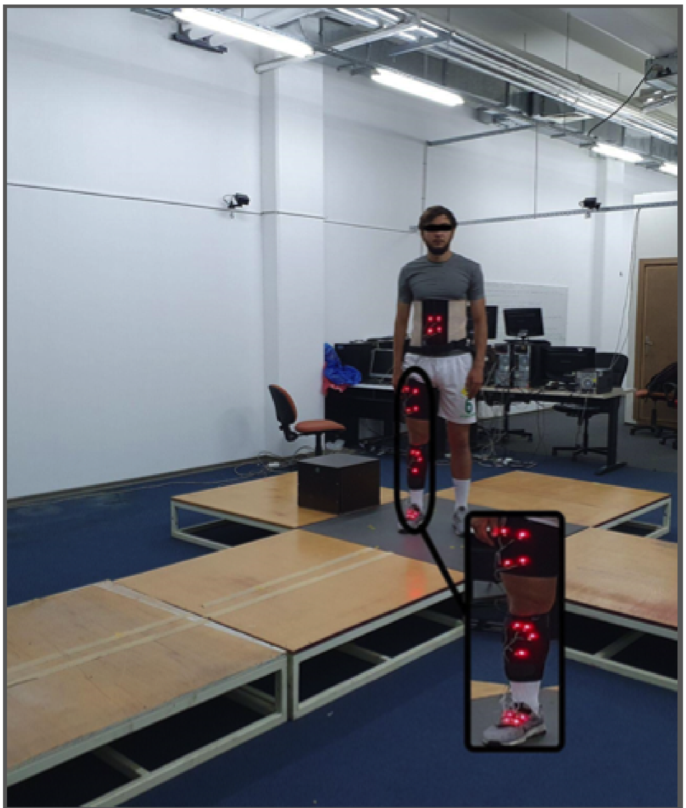

Figure 2. Participant wearing LEDs on body segments

Frequency domain analysis: FFT provides information on the periodic nature of variation in data estimating the strength of each frequency component contained in the measured signal. This analysis gives the opportunity to simply interpret how many different fundamental frequencies possess most of the data power simultaneously. FFT furthermore offers to investigate motor control strategies in sensory-motor performance in the frequency domain (10). Each trial lasted around 1.5 s that caused a peak in the power spectrum (inter-jump frequency) at about 2 Hz (2-4 Hz). Each jump consisted of a preparatory motion (P1) and a flight zone (F1). Intra-jump events in the example caused a faster frequency band at about 6-8 Hz in FFT (Figure 3).

Phase plane representation (phase portrait): Knee joint angular velocity (°/s) was estimated through knee joint angular displacement (°) data. Phase space portraits for the knee joint movement were depicted by using time signals (Figure 3, bottom right). Phase plane representation is a common tool to visualize certain topological characteristics of the dynamicsand to indicate the stability of a nonlinear system. It is a geometrical representation of the trajectories to reveal behavioral characteristics from the kinematic data that would be less evident from time plots of the same data (11-14). Phase plane trajectories of each jump of a participant were presented (Figure 3, bottom right).

Participants settled down within a few hundreds of ms after landing on the plate, creating a vGRF about 2.5-3 times higher than their body weight (Figure 3, top). Reduction in the velocity of knee angular motion can also be observed by plotting the phase portraits of knee joint angular motion trajectories (Figure 3, bottom right: in black). This particular damping behavior demonstrated in the phase plane corresponds to the landing and postural stabilization period of vGRF time series (Figure 3, top). Phase portrait analysis of the knee kinematics was performed to demonstrate inter-jump variability and damping characteristics at landing.

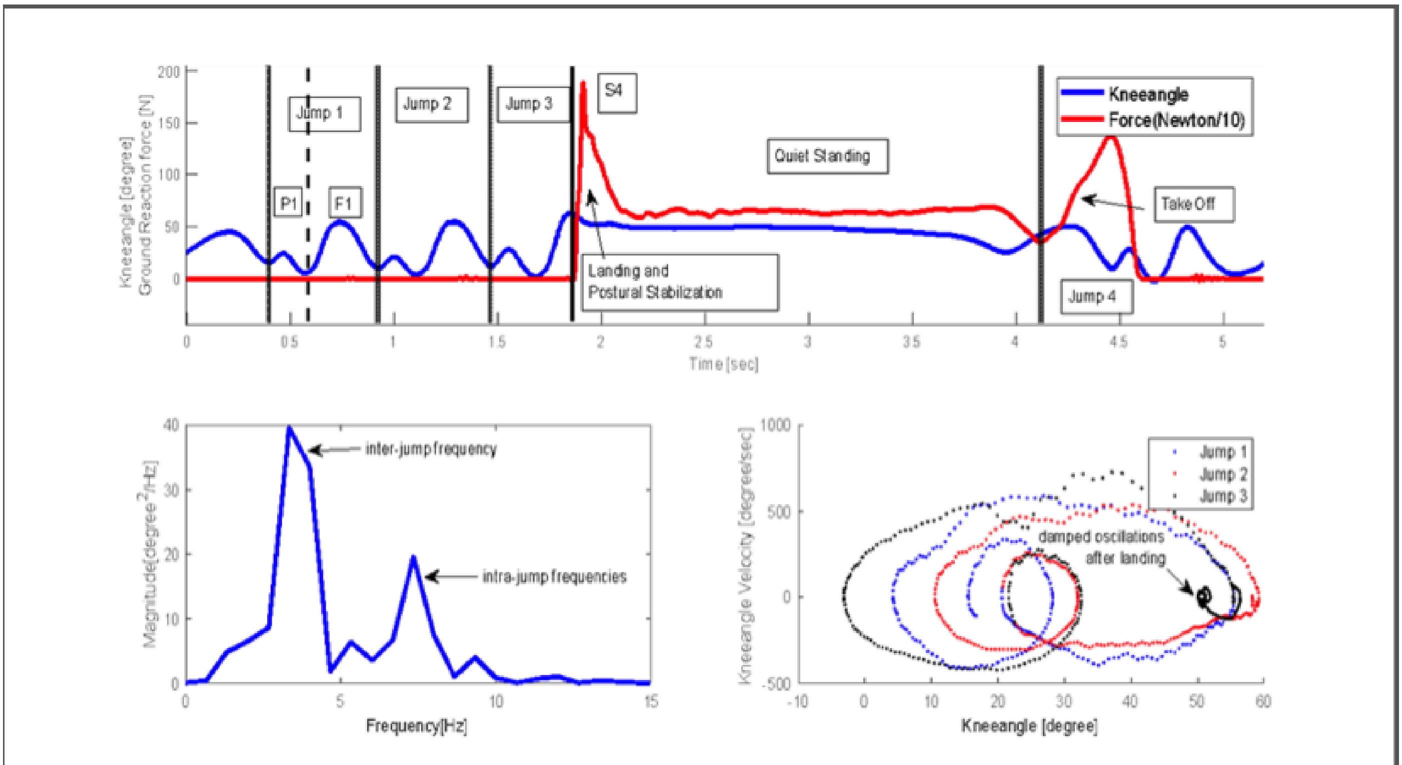

Figure 3. First trial of a participant with the right leg in the SFHT test. Blue line (top): relative knee joint angles, knee flexion (+ angular deflection) and extension (- angular deflection). Red line: vertical GRF (bottom left). Phase plane and FFT presentation of the same data (bottom left and right, respectively).

Statistical Analysis

A manual power analysis using standard formulas revealed that at least eight participants were included ($R=0.48$, Type 1 error (α)=5%, type 2 error (β)=20%. Kinetic and kinematic measures in time and frequency domains from six repeated consecutive trials for SFHT and COHT were compared with repeated measure analysis of variance (ANOVA) across jumps in a trial. Greenhouse-Geisser corrections were used when sphericity assumption was disturbed. Analyses were performed using the IBM SPSS v26.0 software at a significance level of <0.05.

RESULTS

Repeated vGRF normalized to body weight, which was 2.9±0.1 N/kg*10 , was similar [$F(1.9)= 1.290$, $p=0.285$] in both legs in SFHT during repetitions [$F(5.45)=1.340$, $p=0.265$], whereas it was higher in the right (3.13±0.13 N/kg*10) comparing to the left leg (2.92±0.12 N/kg*10) [$F(1.10)=5.127$, $p=0.047$] in COHT during repetitions [$F(5.50)=0.155$, $p=0.977$].

FoT over legs [$F(1.7)=0.244$, $p=0.637$], jumps [$F(3.21)=1.502$, $p=0.261$] and repetitions [$F(5.35)= 0.393$, $p=0.850$] were similar in SFHT. In COHT, FoT over legs [$F(1.9)=0.195$, $p=0.669$] and repetitions [$F(5.45)=1.793$, $p=0.134$] were similar, however FoT over jumps were different [$F(3.27)= 11.006$, $p<0.01$]. In order to explain the different FoT behavior during the jumps between the two tests, preparatory and flight times within a jump were separately analyzed. Preparatory times were found to be shorter in SFHT compared with COHT [$F(1.10)=9.197$, $p=0.013$], whereas flight times were shorter in COHT comparing to SFHT [$F(1.6)=8.998$, $p=0.024$].

Peak flexion [$F(1.9)=0.022$, $p=0.886$], [$F(1.9)=0.284$, $p=0.607$] and extension [$F(1.7)=0.027$, $p=0.874$], [$F(1.9)=0.395$, $p=0.545$] angles of both legs were similar in SFHT and COHT, respectively. Peak flexion [$F(5.45)=0.472$, $p=0.647$], [$F(5.45)=0.253$, $p=0.936$] and extension

[F(5.35)=2.043, p=0.097], [F(5.45)=1.541, p=0.196] angles were similar in SFHT and COHT, respectively, when repetitions were considered. Peak flexion [F(3.27)=4.096, p<0.05] and extension [F(3.21)=6.162, p<0.01] angles were different in SFHT, but were similar in COHT, [F(3.27)=0.858, p=0.475] and [F(3.27)=0.678, p=0.573], respectively, if jumps were considered.

We observed main frequency spectral characteristics at about 2-4 Hz related to inter-jumps. Higher frequency dynamics that we called intra-jump characteristics were also detected. These higher frequency dynamics were considered as the sign of complexity imposed on both tests.

First characteristic peak frequency was similar in both legs [F(1.7)=0.028, p=0.871] and repetitions [F(5.35)=0.874, p=0.508] in SFHT. These were also similar in COHT [F(1.8)=1.665, p=0.233] and [F(5.40)=1.226, p=0.315], respectively. When second characteristic peak frequency was considered, it was similar in both legs in SFHT [F (1.6)= 0.004, p= 0.952]. In repetitions in SFHT [F(5.30)=2.761, p<0.05] however, it was different. Second characteristic peak frequency of both legs [F(1.6)=0.252, p=0.633] and repetitions [F(5.30)=1.189, p=0.338] in COHT was similar. Magnitude of the first characteristic peak frequency was similar in both legs [F(1.7)=0.458, p=0.520] and repetitions [F(5.35)=1.043, p=0.408] in SFHT. They were also similar in COHT [F(1.8)=0.003, p=0.960] and [F(5.40)=1.369, p=0.256], respectively. The magnitude of second characteristic peak frequency was similar in both legs [F(1.6)= 0.976, p=0.361] and repetitions [F(5.35)=1.043, p=0.408] in SFHT, which were also similar in both legs [F(1.6)=0.976, p=0.361] and repetitions [F(5.30)=1.786, p=0.146] in COHT, respectively.

DISCUSSION

Current literature (15-19) has previously assessed ACL injury risk factors such as age, gender, sport type, and structural variables. Biomechanical tools (20,21) additionally allow the calculation and evaluation of joint motion and reaction forces. Knee flexion-extension angles and vertical GRF are among these biomechanical variables. This study focused on generating knee joint angles and GRF in recreational male athletes between the ages of 18-35 years and estimated frequency spectrums and phase portraits at the same time.

Frequency domain metrics and phase portrait analyses in SFHT and COHT are complex and vary between individuals. The same analytical method was used in another study (22) that evaluated complexity and inter-cycle variability of phase portraits of thigh, shank, and foot during gait. One other study (23) underlined the significance of inter-cycle variability suggesting imprints about possible pathological conditions. We proposed that this study could establish a database for SFHT and COHT for GRF, joint kinematics by constructing phase portraits, and estimating frequency domain metrics for personal evaluation in different health conditions.

Participants' joint kinematics were found to be similar in within-subjects statistical tests. Joint kinematics measures however were different between subjects, which acknowledge the existence of a personalized jumping strategy. The mean normalized vertical GRF (FPnorm) was found to be 2.9 (N/kg*10), whereas it was reported as approximately 2.0 in previous studies (24,25). This result was similar for both legs. A previous study reported higher vertical GRF during landing that was associated with ACL injury risk (26). We currently did not evaluate ACLR patients' kinetic data in this study.

We calculated the FoT of four sequential jumps in SFHT and COHT. Our results revealed that FoT was found to be similar in both legs. We observed a difference between the first and fourth comparing to the second and third jumps, which we proposed as due to the momentum gained in forward direction. The possible reason for this observation could be the preparatory postural adjustment in the first and fourth jumps that started from a stationary position. However, the second and third jumps were performed following motion. The period of jumps that started from stationary positions were found to be longer than the jumps performed in motion, whereas the flight times remained similar. Thus, we observed a shorter FoT in the first and fourth jumps in both SFHT and COHT compared with the second and third jumps. Flight time was 0.33 s in a previous study where they used single leg triple hop as a distance test that was consistent with our findings (27).

However, we found significant differences between the dynamic tests. Preparatory and flight periods were significantly different, as participants preferred longer preparatory times but shorter flight times in COHT compared to SFHT despite the fact that the path followed was longer in COHT. Flight time in COHT decreased significantly because linear momentum increased continuously in the forward direction during SFHT, but deteriorated by lateral disturbances in each jump in COHT. On the other hand, after landing from the previous jump, preparatory postural adjustments before takeoff for the next jump lengthened significantly during COHT as the momentum vector changed its direction from cross left to cross right.

The mean peak flexion angle was 55.2° in this study, which was lower comparing to previous studies (28-30). Those studies were based on the maximum jump distance of participants, whereas the current study restricted jump distances to 75% of the leg length to standardize the jumps. This setting can be used for future standard lab measurements.

There were some limitations in the study. Only male participants and recreational athletes of a young age were included. Some previous studies revealed that movement patterns during jumping could be different by gender (31). Results of this study can therefore not be assigned to females and other age groups. Professional athletes were also not included in this study. They may have generated different jumping strategies relevant to their type of sports. Data were optimized based on leg length in our study. There was no optimization based on body mass index, however. We believe that this limitation will not directly affect the kinetic and kinematic data. This kinematic and kinetic study is therefore to be repeated for specific sports when used for return to sport validation.

CONCLUSION

Male recreational athletes' SFHT and COHT presented similar FoT in extremities and repetitions, and first peak frequency characteristics in the spectral distribution of the jumps. Joint kinematics and second characteristic frequency metrics however were unique for each participant. SFHT and COHT on the other hand differed in FoT over jumps, such that preparatory times were found to be longer in COHT, while flight times were shorter. Consequently, the tests were considered repeatable and feasible. Triple hop tests can be recorded at the beginning of the training season for each individual, which can yield a comparative evaluation database for prospective lower extremity injury.

Ethics Committee Approval / Etik Komite Onayı

The approval for this study was obtained from Hacettepe University, Non-Interventional Clinical Researches Ethics Board, Ankara, Türkiye (Decision no: GO20/662 Date: 23.02.2021).

Conflict of Interest / Çıkar Çatışması

Feza Korkusuz, MD is an active member of the Turkish Academy of Sciences (TÜBA).

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Author Contributions / Yazar Katkıları

Author Contributions: Concept - OFI,MI,BCC,SG,FK; Design - OFI,MI,BCC,SG,FK; Supervision - FK,SG,ET,GD; Materials - MI,BCC,SG; Data Collection and/or Processing - OFI,MI,BCC,SG,YM; Analysis and Interpretation - BCC, Literature Review - OFI,YM; Writing Manuscript - OFI,MI,BCC,SG,FK; Critical Reviews - FK,SG

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