ORIGINAL RESEARCH

KINEMATIC AND KINETIC RELIABILITY OF TWO JUMPING AND LANDING PHYSICAL PERFORMANCE TASKS IN YOUNG ADULT WOMEN

Alexis Ortiz, PT, PhD[a,b]
Sharon Olson, PT, PhD[c]
Charles L. Libby, PT, MEd, MS, EMT[c]
Young-Hoo Kwon, PhD[d]
Elaine Trudelle-Jackson, PT, PhD[e]

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ABSTRACT

Background. Jumping and landing tasks are commonly used functional measurement tools to assess lower extremity performance in female athletes. However, few studies have established the number of trials needed to achieve reliability of measurement for evaluating landing mechanics.

Objective. To determine the reliability of peak hip and knee joint angles and peak ground reaction forces during two anterior-posterior unilateral functional tasks performed by young women.

Methods. Sixteen young women (28.5 ± 4.2 years; 162.2 ± 4.8 cm; 59.5 ± 8.1 kg) participated in this investigation. Each participant performed five trials of a 40-cm single leg drop jump and two trials of a ten-repetition, 20-cm, single leg up-down hop task during the same session. Peak hip and knee joint angles, peak vertical ground reaction forces, and ground contact time were measured. Intraclass correlation coefficients (ICC), standard errors of measurement, and 95% confidence intervals were calculated for all variables measured during multiple trials for both tasks.

Results. The five-trial mean ICC values of the drop jump were ≥ 0.75 for all variables. The single and two to four-trial average ICC values yielded good reliability for only some variables. Single-trial and two-trial mean ICC values for the up down test were ≥ .77.

Discussion and Conclusion. The use of five-trial averages for the 40-cm drop jump and a single trial for the 20-cm, up-down hop task showed that for these functional tasks performed by young adult women, reliable measurement of lower extremity landing mechanics can be achieved.

Key Words: reliability, kinematics, landing, kinetics, hop test

[a] School of Physical Therapy
College of Health Related Professions
University of Puerto Rico, Medical Sciences Campus
San Juan, PR

[b] Department of Physical Medicine, Rehabilitation, and Sports Medicine, School of Medicine
University of Puerto Rico, Medical Sciences Campus
San Juan, PR

[c] School of Physical Therapy, Texas Woman's University
Houston, TX

[d] Department of Kinesiology, Texas Woman's University
Denton, TX

[e] School of Physical Therapy, Texas Woman's University
Dallas, TX

CORRESPONDENCE:
Alexis Ortiz, PT, PhD, CSCS
Assistant Professor
School of Physical Therapy
Medical Sciences Campus
University of Puerto Rico
PO Box 365067
San Juan, PR 00936-5067
(787) 758-2525 x. 4201
Fax: (787) 753-7262
alexisortiz@cprs.rcm.upr.edu

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INTRODUCTION

Women athletes experience higher knee joint injury rates compared to men in all sports.[1-3] Study of lower extremity movement using three-dimensional motion analysis can contribute to the understanding of their knee injuries. Various functional tasks have been described by several investigators for analyzing lower extremity performance, especially when studying landing mechanics in young women. Functional tasks are ideal assessment tools since these tasks integrate several performance components such as joint mobility, muscle strength, power, proprioception, neuromuscular control, balance, and agility.[4-6] However, most of the lower extremity tasks assessed with motion analysis in previous investigations have been bilateral landing tasks in men, or a combination of men and women.[7, 8] While bilateral tasks provide good information regarding lower extremity performance, these tasks could be missing critical unilateral events that are commonly experienced during sports.[9-11] In most sports maneuvers, one limb encounters greater loads than the contralateral limb, even during bilateral activities such as cutting and pivoting.[9,10]

Investigators who conduct motion analysis research rarely report reliability estimates for analyzed tasks. Reliability refers to the reproducibility of the measurement and the ability to minimize measurement error, guaranteeing more accurate data.[4,6,12-14] Investigators who have addressed reproducibility for kinematic variables have primarily assessed bilateral landing tasks in men and women participants combined.[7,8] Researchers who have assessed reliability of both kinetic and kinematic variables during bilateral jump tasks performed by both sexes combined have calculated intraclass correlation coefficients (ICC's) of 0.89 and above.[7,8]

Reliability values for single-leg tasks can be found in the literature but are limited because the focus has been only for jumping distance and time measures.[4-6,15-17] No reliability values, measurement error estimation, or number of trials needed have been previously assessed for kinematic and kinetic variables during single-leg tasks. Furthermore, performance during single-leg tasks is influenced by external factors such as practice, confidence, fatigue, and number of trials.[11,13,18] Greater reliability values have been reported when the average of selected trials was representative of 100% performance effort, which was not achieved until several practice trials had been taken.[18] Several practice trials improve confidence and learning of the task.[4,12,18] However, large numbers of trials may also increase the time during data collection and the risk of injuries during task performance.[16,18] The researchers attest that during development and assessment of research protocols involving human participants, efforts should be made to maximize performance during testing procedures by allowing sufficient warm-up and an adequate number of trials.[5]

The purpose of this investigation was to determine reliability of peak hip and knee joint angles and peak ground reaction forces during two single-leg jumping and landing tasks in healthy young women in order to determine the number of trials needed to achieve acceptable reliability. Data was collected for hip flexion, hip adduction, hip internal rotation, knee flexion, knee valgus, knee external rotation, and vertical ground reaction force measures during a single-leg, 40-cm drop jump and a single-leg, 20-cm up-down hop task. A secondary purpose was to examine potential differences in these measures between the dominant and non-dominant legs.

METHODS

Participants

Sixteen physically active young adult women (age: 28.5 ± 4.2; height: 162.2 ± 4.8 cm; weight: 59.5 ± 8.1 kg) engaged in fitness activities such as jogging and weightlifting participated in this study. Participants were physical therapy students. Exclusion criteria were any history of back or lower extremity surgery and recent injury in the lower back or lower extremities over the past six months. Each participant read and signed an informed consent approved by Texas Woman's University Institutional Review Board prior to participation. All participants were asked to perform a single hop for distance and a cross-over hop for distance as a screening procedure to obtain clearance for participation. Ability to stick the landing with no report of giving away of the knee during both functional screening tasks were used as criteria for participation and inclusion in the study.

Instrumentation

Participants had 12 retro-reflective markers attached to the skin. These markers were placed over the following landmarks: bilateral anterior superior iliac spines; the second sacral vertebra; bilateral greater trochanters; bilateral lateral femoral epicondyles; bilaterally, mid-distance between the greater trochanters and lateral femoral epicondyles; bilateral medial femoral epicondyles; bilateral lateral malleoli; bilaterally, mid-distance between the lateral femoral epicondyles and lateral malleoli; bilateral medial malleoli; bilateral calcaneal tuberosities; and bilateral second metatarsophalangeal joints.

The motion analysis system consisted of four digital cameras (60-Hz sampling rate) time-synchronized to one force plate (AMTI, Watertown, MA) (1000 Hz sampling rate). Video data was captured with APAS CapDV software (Ariel Dynamics, Inc. San Diego, CA). Force plate data was recorded with APAS Analog software (Ariel Dynamics, Inc. San Diego, CA). Prior to data collection, space was calibrated according to the manufacturer's recommendation using a Direct Linear Transformation algorithm with an 8-point, 81.5-cm3 cube. A static trial was captured with each participant standing still, with arms across the chest, to align the joint coordinates to the laboratory recording instruments. After the static trial, the medial femoral epicondyle and medial malleolus markers were removed, to prevent interference between markers and the lower extremities during the performance trials.

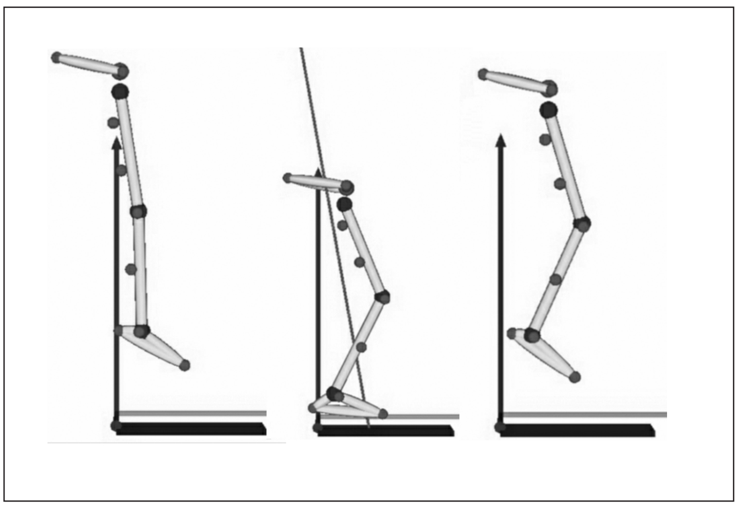

Figure 1: *40-cm single-leg drop jump. Each participant dropped from a 40-cm box onto the force plate. Each participant performed a maximal vertical jump upon landing.*

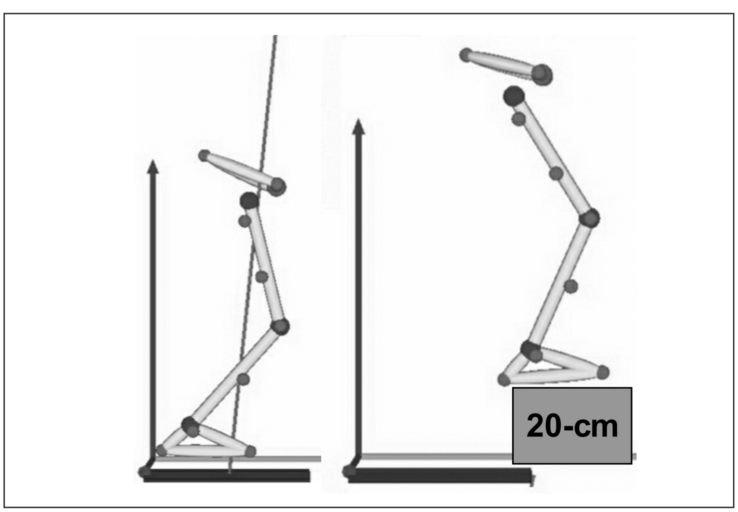

Figure 2: *20-cm up-down hop task. Each participant jumped up-to and down-from a 20-cm box ten consecutive times. The middle six jumps were averaged and used for analysis.*

Procedures

Weight, height, and the distance between anterior superior iliac spines were measured in each participant. The hip joint center was calculated using the distance between the anterior superior spines and Kwon 3D software (VISOL Inc., Seoul,Korea).[19-21] Leg dominance was determined by the leg preferred to perform a single hop for distance.

The warm-up protocol consisted of five minutes of cycling at 40 to 60 rpm on a cycle ergometer, 10 half squats, and five continuous vertical jumps. In addition, each participant performed two practice trials with the dominant and non-dominant limbs for both jump tasks. Before participants performed these practice trials, a member of the research team demonstrated both tasks. Two practice trials following demonstration of functional tasks have shown to be sufficient for reliable results during performance of functional tasks.[16] The jump tasks utilized in this investigation consisted of a 40-cm single-leg drop jump *(Figure 1)* and a ten-repetition, single-leg, 20-cm up-down hop task *(Figure 2)*. These tasks were randomly ordered. A total of five trials for the drop jump and two trials of the up-down task were performed during the same session. The drop jump was selected for its ability to create large eccentric loading on the lower extremities.[22] The up-down task was selected because of its sensitivity, specificity, and accuracy (58%, 97%, and 80%, respectively) in diagnosing dynamic knee instability.[23]

The drop jump *(Figure 1)* consisted of initially standing with both feet on the 40-cm platform and standing on the jumping leg when the command "on your mark" was given. After the command "set", the participant was instructed to drop down when she felt ready to do so. No additional instructions on how to stand on the drop jump box were given. Each participant was told not to jump vertically, but drop from the box. If the participant performed a vertical jump that was visible to the researchers, the trial was repeated. Each participant was instructed to perform a maximal effort vertical jump upon landing, single-leg, on the center of the force plate. Participants were allowed to use arms freely during all moments of the drop jump. Each participant was allowed to rest as long as she wanted between trials and tasks. Researchers did not allow participants to take less than one minute of rest between trials and tasks.

For the up-down hop task *(Figure 2)*, the participant performed ten repetitive single-leg hops, up to and down from a 20-cm step. As developed by Itoh et al[23], this task began with each participant standing in front of the 20-cm step. As soon as she felt ready to do so, she jumped single-leg up to and down from the 20-cm step ten consecutive times. The ten consecutive up and down hops comprised one trial. Participants were allowed to use arms freely during all moments of the up-down hop task. Due to the high demands imposed on the lower extremities during this task, participants were required to perform this task only twice. Resting time between trials was similar to the drop jump.

Data Reduction

Joint angles were synchronized and analyzed with Kwon3D 3.1 software (VISOL Inc., Seoul, Korea). Synchronizing events were detected by the moments of initial contact and push-off from the force plate. Joint angles were derived and calculated from the three-dimensional trajectory of the retro-reflective markers. Frequency contents were initially screened using residual analysis and then filtered through a second order, low-pass Butterworth filter (6 Hz).[24] Hip and knee joint angles were defined in the sagittal, frontal, and transverse planes as the first, second, and third rotations, respectively. Local reference frames fixed to the body were defined based on the markers and joint centers for the pelvis, thigh, shank, and the foot. Rotational transformation matrices between linked segments were computed based on the unit vectors of the local frames: pelvis to thigh (hip joint), thigh to shank (knee joint), and shank to foot (ankle joint). Euler angles (orientation angles) were computed from the rotational transformation matrices using the ML-AP-longitudinal axis (XYZ) rotation sequence.

Peak hip flexion, adduction, and internal rotation, and peak knee flexion, valgus, and external rotation were measured. In addition, peak vertical ground reaction forces and ground contact time were assessed. Joint angles and ground reaction force data were exported to Microsoft Excel™ for analysis. Peak values were identified as the greatest value for all variables from the moment each participant landed on the force plate through the moment she left the force plate into the vertical jump. Peak hip and knee joint angles and peak ground reaction forces were chosen as key variables of interest given these measurements are related to the main injury-causing factors to the knee joint.[10]

From the total of ten continuous hops for the up-down hop task, the first two and last two jumps were excluded to account for acceleration and deceleration during the performance task, averaging the middle six jumps for analysis. This method of exclusion has been shown to help control for performance variability during physical performance tasks including multiple repetitions.[25] The up-down data included the same peak joint angles and kinetic variables as the drop jump. The mean peak values of the middle six hops were considered for analysis.

Data Analysis

All kinematic and kinetic data were screened for normality assumptions and outliers using the Kolmogorov-Smirnov test and histograms. Means, standard deviations, intraclass correlation coefficients (ICC), standard errors of measurement (SEM), and 95% confidence intervals (CI) around the mean and ICC values among the trials in both tasks were calculated for the following measures: hip flexion, hip adduction, hip internal rotation, knee flexion, knee valgus, knee external rotation, vertical ground reaction forces, and contact time during landing. Mean values for peak joint angles and vertical ground reaction forces during the landing phase were used for analysis.

Repeated measures multivariate analyses of variance for mean peak values for five trials of the drop jump and mean peak values for two trials of the up-down task were conducted to determine any significant differences in peak hip and knee joint angles, ground reaction forces, and contact time between the dominant and non-dominant limbs. Given that no significant differences between dominant and non-dominant legs were found, only the dominant leg was considered for the reliability analysis.

Repeated measures analyses of variance for the dominant limb were performed to develop within-session intraclass correlation coefficients for the averages of two to five trials of the drop jump (ICC [3, k]) and for the two-trial average of the up-down hop task (ICC [3, 2]). Intraclass correlation coefficients for a single trial (ICC [3, 1]) were calculated based on the number of multiple trials by using the following formula: between subjects mean square – error mean square / between subjects mean square + (k-1) error mean square.14

RESULTS

Means, standard deviations, ICC values, SEMs, and 95% CIs for the drop jump and up-down hop task are presented in Tables 1 and 2, respectively. The five-trial averages of the drop jump (Table 1) showed good reliability for all joint angles (ICC ≥ .75) and kinetic (ICC ≥ .86) measures. The single trial and 2, 3, and 4-trial averages yielded good reliability for some of the kinematic and kinetic variables for the drop jump, but not all. The single trial and 2-trial averages for the up-down task (Table 2) showed good reliability for all joint angles (ICC ≥ .77) and kinetic (ICC ≥ .86) measures.

DISCUSSION

The purpose of this investigation was to evaluate the number of trials needed to achieve acceptable reliability when assessing kinematic and kinetic variables during two single-leg tasks in young women. In sports physical therapy, single-leg testing using functional tasks such as the ones used in this investigation help detect muscle weaknesses and knee instabilities to a much greater extent than bilateral functional testing.[23] Several components such as practice, familiarization, and confidence of the participant are necessary to perform functional tasks in an optimal manner.[16,18] The researcher and sports physical therapist need to be aware how testing procedures could be performed in a more reliable manner and how reliability could be affected by several extraneous variables. Using the average score of multiple trials may improve reliability but may likely also increase the possibility of fatigue and increase the time for data collection and analysis.[26] Therefore, a balance between the number of trials to obtain reliable results and feasibility in terms of fatigue and time management is needed during the measurement process.

The results of this investigation suggest that several trials are needed but the number of trials differs according to the specific movement and task analyzed. If tri-planar movements of the hip are considered during the drop jump, four trials are sufficient for reliable results, with hip internal rotation showing the lowest ICC value (0.81). When peak knee joint angles are assessed during the drop jump, five trials are recommended for reliable results in all three planes of motion, with knee flexion exhibiting the lowest ICC value (0.75). During the up-down hop task, a single trial exhibited good reliability for all hip and knee peak joint angles (>0.77). Therefore, these two tasks can be used as functional research tools in this population in a reliable manner for tri-planar hip and knee motion if five trials of the drop jump and a single trial of the ten-repetition up-down task are used to achieve ICC values greater than 0.75.[11]

Multiple factors could have affected each participant's performance across trials. One of the most common factors thought to affect reliability of measurements is fatigue during testing procedures.[5,12] Fatigue has shown to impair physical performance[27] and affect reliability of hop testing.[11] Augustsson et al[11] assessed test-retest reliability of 11 male participants during a single-hop for distance during non-fatigued and fatigued sessions performed on separate days. The non-fatigue session comprised of performing the single-leg hop task after a warm-up protocol. During the fatigue session, each participant performed the single-leg hop task after a knee extensor fatigue protocol in a dynamometer. Participants performed three trials of a single-leg hop for distance on each of the sessions. The researchers found that within-trials reliability for the non-fatigue session was higher (ICC = 0.98) than the reliability values for the fatigue session (ICC = 0.75). However, when participants were retested three minutes after finishing the fatigue session hop tasks values were similar to the non-fatigue state exhibiting almost full recovery.[11] In this investigation, to prevent the possible effects of fatigue on each participant's performance, each woman was allowed to rest as long as she needed before performing

Table 1. *Kinematic and kinetic reliability values for the drop jump*

	Trials				
	Mean (º) ± SD **95% CI (º)** **ICC (SEMº)** **ICC 95% CI**	**Mean (º) ± SD** **95% CI (º)** **ICC (SEMº)** **ICC 95% CI**	**Mean (º) ± SD** **95% CI (º)** **ICC (SEMº)** **ICC 95% CI**	**Mean (º) ± SD** **95% CI (º)** **ICC (SEMº)** **ICC 95% CI**	**Mean (º) ± SD** **95% CI (º)** **ICC (SEM∞)** **ICC 95% CI**
Kinematics	***Single Trial***	***2-Trial Avg***	***3-Trial Avg***	***4-Trial Avg***	***5-Trial Avg***
Hip flexion	55.13 ± 12.06 45.38-64.88 .83[a] (4.97) .55-.94	54.66 ± 12.23 47.47-61.85 .91 (3.67) .71-.97	54.41 ± 11.85 49.22-59.60 .95 (2.65) .88-.98	54.12 ± 11.80 50.11-58.13 .97 (2.04) .93-.99	53.76 ± 12.04 50.42-57.10 .98 (1.70) .95-.99
Hip adduction	13.47 ± 5.19 8.38-18.56 .75[a] (2.60) .39-.91	11.74 ± 4.87 8.17-15.31 .86 (1.82) .56-.95	10.95 ± 5.04 8.34-13.56 .93 (1.33) .84-.98	10.61 ± 5.20 7.91-13.31 .93 (1.38) .85-.98	10.43 ± 5.30 8.11-12.75 .95 (1.19) .88-.98
Hip internal rotation	11.27 ± 9.24 0-24.33 .48[a] (6.66) -.05-.80	12.01 ± 9.66 0.81-23.31 .65 (5.71) -.10-.89	11.37 ± 8.24 2.98-19.76 .73 (4.28) .33-.91	10.81 ± 7.68 4.25-17.37 .81 (3.35) .59-.93	10.54 ± 7.59 5.39-15.69 .88 (2.63) .73-.95
Knee flexion	63.46 ± 10.78 43.30-83.62 .09[a] (10.28) -.44-.58	60.11 ± 6.82 47.86-72.36 .16 (6.25) -1.61-.73	59.60 ± 5.73 50.14-69.06 .29 (4.83) -.73-.75	59.82 ± 6.05 52.41-67.23 .61 (3.78) .12-.86	60.04 ± 6.43 53.74-66.34 .75 (3.22) .46-.91
Knee valgus	10.44 ± 4.42 3.40-17.48 .34[a] (3.59) -.20-.73	9.83 ± 3.59 4.90-14.76 .51 (2.51) -.52-.84	9.54 ± 3.40 6.08-13 .73 (1.77) .34-.91	9.58 ± 3.46 6.87-12.29 .84 (1.38) .63-.94	9.60 ± 3.36 7.14-12.06 .86 (1.26) .70-.95
Knee external rotation	11 ± 7.79 3.21-18.79 .74[a] (3.97) .36-.91	10.65 ± 6.71 5.56-15.74 .85 (2.60) .53-.95	10.76 ± 7.06 7.10-14.42 .93 (1.87) .82-.97	10.79 ± 7.46 7.87-13.71 .96 (1.49) .90-.98	10.78 ± 7.52 8.23-13.33 .97 (1.30) .94-.99
Kinetics					
GRF (BW)	4.79 ± .89 3.67-5.91 .59[a] (.57) .08-.85	4.66± .81 3.86-5.46 .74 (.41) .15-.92	4.64 ± 1.04 3.89-5.41 .86 (.40) .65-.95	4.74 ± 1.07 4.18-5.30 .93 (.28) .84-.98	4.27 ± 1.00 3.75-4.79 .93 (.27) .85-.98
Contact time (seconds)	.043 ± .011 .04-.05 .70[a] (.003) .26-.90[a]	.038 ± .008 .03-.05 .82 (.004) .42-.95	.038 ± .008 .03-.04 .85 (.003) .61-.95	.039 ± .008 .03-.04 .91 (.002) .78-.97	.040 ± .008 .04-.04 .94 (.002) .86-.98

SD: standard deviation; ICC: Intraclass Correlation Coefficient; SEM: standard error of measurement estimated using SD of the score; 95% CI: confidence interval based on SEM; GRF: ground reaction forces/times body weight. [a] Intraclass correlation coefficients for a single trial (ICC [3, 1]) were calculated based on the number of multiple trials used by the following formula: between subjects mean square – error mean square / between subjects mean square + (k-1) error mean square (Figure 3).[14]

Table 2. *Kinematic and kinetic reliability values for the up-down hop test*

	Trials	
Kinematics	**Mean (º) ± SD** **95% CI (º)** **ICC (SEMº)** **ICC 95% CI** ***Single Trial***	**Mean (º) ± SD** **95% CI (º)** **ICC (SEMº)** **ICC 95% CI** ***2-Trial Avg***
Hip flexion	36.95 ± 7.56 36.34-42.96 .95[a] (1.69) .82-.99	38.69 ± 7.37 36.19-41.19 .97 (1.28) .90-.99
Hip adduction	9.72 ± 7.42 5.87-13.57 .93[a] (1.96) .76-.98	9.14 ± 7.17 6.71-11.58 .97 (1.24) .87-.99
Hip internal rotation	7.59 ± 7.53 5.04-10.15 .97[a] (1.30) .89-.99	7.78 ± 7.42 5.72-9.84 .98 (1.05) .94-1.0
Knee flexion	51 ± 4.25 47.01-54.99 .77[a] (2.04) .36-.94	49.55 ± 5.39 45.74-53.36 .87 (1.94) .53-.97
Knee valgus	7.49 ± 5.97 4.63-10.36 .94[a] (1.46) .79-.99	6.25 ± 4.88 4.59-7.90 .97 (.85) .88-.99
Knee external rotation	10.12 ± 8.09 5.92-14.32 .93[a] (2.14) .76-.98	8.96 ± 7.93 6.27-11.65 .97 (1.37) .86-.99
Kinetics *GRF (BW)*	2.67 ± .57 2.29-3.06 .88[a] (.20) .65-.96	2.80 ± .39 2.61-2.99 .94 (.10) .79-.98
Contact time (seconds)	.04 ± .03 .03-.05 .97[a] (.01) .91-.99	.07 ± .02 .07-.08 .99 (0.0) .95-1.0

SD: standard deviation; ICC: Intraclass Correlation Coefficient; SEM: standard error of measurement estimated using SD of the score; 95% CI: confidence interval based on SEM; GRF: ground reaction forces/times body weight. [a] Intraclass correlation coefficients for a single trial (ICC [3, 1]) were calculated based on the number of multiple trials used by the following formula: between subjects mean square – error mean square / between subjects mean square + (k-1) error mean square (Figure 3).[14]

the next trial. Although sufficient rest was allowed between trials, the possibility of cumulative fatigue throughout the testing session could not be dismissed.

The 60 Hz sampling rate could have introduced variability into the measurement of such fast movements. However, the high frequency components for the drop jump and up-down jump tasks, especially during impact with the force plate capable of introducing such variability, were filtered through the 6 Hz low-pass filter. Therefore, the 60 Hz sampling rate with a 6 Hz Butterworth filter seems reasonable given the data of interest were peak hip and knee joint moments during the ground contact phase.

Perry et al[18] assessed the number of trials during hop tests needed for reliable distance and height measures in individuals with anterior cruciate ligament deficiency and ACL reconstruction. The researchers reported that for the single-hop for distance and triple crossover tasks, a minimum of 10 trials ensured 99% of maximum performance effort values in both tasks. Similarly, a minimum of 15 trials were needed to ensure 97.6% of maximum performance effort during the vertical single-leg jump. The number of trials needed in a research protocol are important if accurate results are expected and if the trials are indeed representative of maximum performance.[18] The results of the current investigation showed results similar to Perry et al[18] in terms of total number of jumps needed for acceptable reliability.

Previous investigations evaluating landing performance in young women during bilateral landing tasks used three to five trials and reported good ICC values for knee joint kinematics and kinetics without a comprehensive warm-up.[7,8] No investigations of reliability for kinematic and kinetic variables have reported SEM or 95% CI values.[7,8] These statistics indicate the trial-to-trial error expected in the functional tasks and determine the range for a population's true score.[12] Known error scores help the researcher assess whether changes in participants' performance are really true changes or are within the range of error for the specific measurement.[4,12] In addition, these statistics allow observation of the improvements in reliability values with greater number of trials *(Tables 1-2)*.

Typically, only the dominant leg is used as reference for biomechanical analysis and to make group comparisons when evaluating lower extremity landing mechanics. The findings of this investigation suggest that in non-injured young women, either the dominant or non-dominant leg may be considered as reference for analysis. These findings are consistent with other investigations in which no statistically significant differences between the dominant and non-dominant legs were found for lower extremity joint angles,[25] muscle strength,[28] and endurance[28] during physical performance tasks.

Several practical applications exist that could be derived from this investigation. First, the process of familiarization and warm-up should be included in testing protocols to ensure near maximum performance. In addition, the use of multiple trial or multiple repetition averages enhances the reliability of the measurements and reduces the absolute measurement error. The protocol used in this investigation was acceptable for reliably testing single-leg landing mechanics in young women. Because ligamentous injuries have been shown to occur mainly during unilateral tasks, single-leg functional tasks should be incorporated into biomechanical assessments of performance.

CONCLUSIONS

The results of this investigation revealed that the average of five trials of the drop jump and one trial of the 10-repetition up-down task are recommended to obtain good trial-to-trial reliability for hip and knee peak joint angles and ground reaction forces. Additionally, in healthy non-injured individuals either dominant or non-dominant legs could be used to assess landing mechanics.

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