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ORIGINAL ARTICLE

Reliability of unipodal and bipodal counter movement jump landings in a recreational male population

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Abstract
Movement patterns during landing have been suggested to be related to injury risk. The purpose of this study was to determine the inter-session reliability of kinematic variables and ground reaction forces during landing in a population of male recreational athletes after a counter movement jump. Both unipodal and bipodal landings were evaluated. Furthermore, the possibility to improve landing reliability with a verbal instruction was also studied. Twenty-four male volunteers with no history of lower extremity trauma were randomly assigned to two groups (with and without verbal landing instruction). An optoelectronic 3D system and force plates were used to measure the lower limb joint angles and the ground reaction forces during landing. Intraclass correlation values show moderate to excellent inter-session reliability for the bipodal task (ICC average: 0.80, range: 0.46–0.97) and poor to excellent reliability for the unipodal task (ICC average: >0.75, range: 0.20–0.95). However, large standard errors of measurement values at the ankle joint at impact (27.6 ± 11.5°) and for the vertical ground reaction forces (394 ± 1091 N) show that some variables may not be usable in practice. The verbal instruction had a negative effect on the reliability of unipodal landing but improved the reliability of bipodal landing. These findings show that the reliability of a landing task is influenced by its motor complexity as well as the instruction given to the subject.

Keywords: *Biomechanics, lower limb, kinematics, ground reaction forces, verbal instruction*

Highlights
- Movement patterns during landing have been suggested to be related to injury risk.
- The purpose of this study was to determine the inter-session reliability of kinematic variables and ground reaction forces.
- The reliability of a landing task is influenced by its motor complexity as well as the instruction given to the subject.

Introduction

A key factor for kinematic and kinetic evaluations is the ability to obtain reliable measurements. Evaluations based on landing tasks are a common way to assess the risk of injury. Among others, Anterior Cruciate Ligament (ACL) injuries often occur during landing or cutting motions in the absence of contact with another player (Hootman, Dick, & Agel, 2007). Variables of interest for injury prevention in the literature include (1) angular position, angular velocity, moment of the joints of the lower limbs (Ekegren, Miller, Celebrini, Eng, & Macintyre, 2009; Ford, Myer, & Hewett, 2007; Padua et al., 2011), and of the trunk (Padua et al., 2011), (2) ground reaction forces (Milner, Westlake, & Tate, 2011), and (3) temporal variables (Ross, Guskiewicz, & Yu, 2005).

A landing task is characterised by several factors including, among others, the type of initial jump, the landing leg(s), the instructions given. Studies of the literature have considered the reliability of several landing tasks. Concerning the type of initial jump, landing tasks based on stop jumps (Padua

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et al., 2011), drop jumps (Ford et al., 2007), single leg landing (Alenezi, Herrington, Jones, & Jones, 2014), and single leg cross landing (DiCesare et al., 2015) were found to have good to excellent reliability concerning biomechanical variables. Despite the counter movement jump is one of the most used jumps in numerous sports including basketball, volleyball, and soccer, few studies (Cámara et al., 2011) have evaluated its reliability.

Concerning the landing leg(s), bipodal (Ekegren et al., 2009; Ford et al., 2007; Padua et al., 2009) versus unipodal (Dingenen, Malfait, Vanrenterghem, Verschueren, & Staes, 2014; Munro, Herrington, & Carolan, 2012) landing is another distinguishing feature of the landing tasks described in the literature. Some studies demonstrate that evaluating unipodal landing may provide valuable information. For instance, Munro et al. showed that female basketball and football players display greater knee valgus during unipodal landing (in comparison to bipodal landing) and concluded that injury prevention programmes should include unipodal landing evaluation (Munro, Herrington, & Comfort, 2012). Similar results were found in a study by Pappas et al. (Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007). There is, therefore, an interest in studying both the bipodal and the unipodal landing of counter movement jumps.

The instructions given to the athlete before the task may influence the performance/quality of a task and possibly its reproducibility. Concerning landing, verbal tasks have been mostly used to reduce the ground reaction forces and consequently the risk of injury. Milner et al. were able to improve the landing pattern after a jump thanks to a verbal instruction (Milner, Fairbrother, Srivatsan, & Zhang, 2012). Similarly, McNair et al. showed that verbal instructions as well as auditory cues were effective in reducing the ground reaction forces at impact (McNair, Prapavessis, & Callender, 2000). In these latter examples, the goal pursued was achieved by making the volunteers aware of procedural processes. However, verbal instructions may also have implicit goals: the volunteer is not aware of the objective pursued. Such methodology is a widespread practice in psychology to evaluate, for instance, the effect of negative or positive stereotype threats (Beilock & McConnell, 2004). Providing verbal instructions, which do not directly concern the landing, could therefore be a possible way to indirectly improve landing reliability while preserving natural kinematics.

In addition to the characteristics of the landing task, the level of the athletes should also be considered. Because novice athletes have more limited perceptual-motor skills than expert athletes (Wright, Bishop, Jackson, & Abernethy, 2010), it may not be possible to derive the reliability of recreational practitioners' landings from the elite athletes. Even if both elite and recreational practitioners are concerned with lower limb injuries, reliability studies have mainly focused on athletes playing at a competition level (Dingenen et al., 2014; Ford et al., 2007). However, focusing on recreational athletes, as Alenezi et al. (2014) did, is important as they represent a considerable number of injuries. Stevenson et al. report in Western Australia that half of the participants (non-professional level) sustained at least one injury during five months of study (Stevenson, Hamer, Finch, Elliot, & Kresnow, 2000). In the United Kingdom, an incidence of about 30 cases of ACL injury per 100,000 people per year is observed in the global population (Bollen, 2000).

Finally, post-processing of the results, such as averaging the biomechanical variables across multiple trials, may also influences the intra-session variability evaluation. Most of the reliability studies concerning landing chose to average several trials (DiCesare et al., 2015; Ford et al., 2007; Milner et al., 2011; Padua et al., 2011). However, averaging across multiple trials may lead researchers to disregard extreme motions, which should be detected from a prevention of injury point of view. The gain in reliability should be sufficient to justify averaging several trials. To our best knowledge, no study has evaluated the effect of averaging several trials on the reliability of kinematic and kinetic variables during landing.

This study focused on the reliability of kinematic and kinetic variables during the landing phase of a counter movement jump in a population of recreational athletes. The influence of two conditions was investigated in particular: (1) the influence of performing unipodal versus bipodal landings and (2) the influence of a verbal instruction. A sub-aim of the study was to evaluate the effect of averaging several trials on the reliability of the biomechanical variables.

Methods

Twenty-four male volunteers participated in this study. The inclusion criteria were: age between 18 and 30 years old, the absence of history of serious lower limb trauma (fractures, meniscus or ligament tears), and between 1 and 3 hours of sport activity per week. The rationale for the volume of sport activity used as an inclusion criterion was to ensure that the volunteers would be physically active but would not be involved in higher divisions/leagues. The volunteers were involved in soccer (50%), rugby (17%), local tennis clubs (17%), and other sports (boxing, judo). Participants were then randomly assigned to one of two groups ("instruction" or "no instruction"). Demographic characteristics were as follows: "instruction" 22.7 ± 2.5 years; 74.2 ± 12.9 kg; 1.79 ± 0.03 m and "no instruction" 22.6 ± 0.8 years; 81.8 ± 9.8 kg; 1.83 ± 0.04 m. The study complies with the Declaration of Helsinki and was approved by the institutional ethical committee.

Each volunteer was instrumented with 16 markers attached on the lower limbs (great trochanters, lateral femoral epicondyles, lateral malleoli, heels, fifth metatarsophalangeal joints, big toes) and on the pelvis (both anterior and posterior superior iliac spines). The markers' 3D positions were measured using four Codamotion CX1 units (Charnwood Dynamics, Rothley, UK) at a sampling rate of 200 Hz. Ground reaction forces were measured separately for each foot using two force plates (Kistler™ type 9281 EA, Kistler AG, Switzerland) at a sampling rate of 1000 Hz.

Before the tests, all volunteers executed a standardised warm-up, consisting of six minutes on an ergocycle (50 W resistance), two series of 30 steps on a 20-cm box, and finally two series of 10 half-squats. Before each task, the volunteers were invited to perform one or two practice trials to confirm that the instructions were fully understood. After warm-up and familiarisation with the tasks, the volunteers were asked to perform three maximal counter movement jumps (Figure 1) for each of the following conditions: (i) bipodal jump, (ii) unipodal jump on the dominant side (kicking leg), (iii) unipodal jump on the non-dominant side. To neutralise any coordination effects between the lower and upper limbs, the volunteers were asked to hold a wooden stick on their shoulders (Bazett-Jones, Finch, & Dugan, 2008). The neutralisation of the upper limbs also increased the need for trunk stabilisation during the jumping and landing phases. All tests were performed twice at a one-week interval and at the same time of the day to avoid any impact of circadian rhythmicity (Drust, Waterhouse, Atkinson, Edwards, & Reilly, 2005).

Both groups were asked to jump as high as possible but only the second group was verbally instructed to anticipate an additional action after the landing phase ("land as if you will need to receive a ball and/or sprint"). No additional action actually occurred. The rationale for providing an instruction was to force the volunteers to focus on the task until the end of the reception phase. However, the landing instruction was deliberately vague as we did not want participants to alter their landing technique. This natural landing technique is probably the one used during sport activities and is consequently representative of their risk of injury.

For each condition, analyses were performed on both the highest jump and on the mean of the three trials. 3D marker positions were filtered through a zero-phase 4th order low-pass Butterworth filter at a cut-off frequency of 10 Hz. Initial contact was defined when vertical ground reaction forces

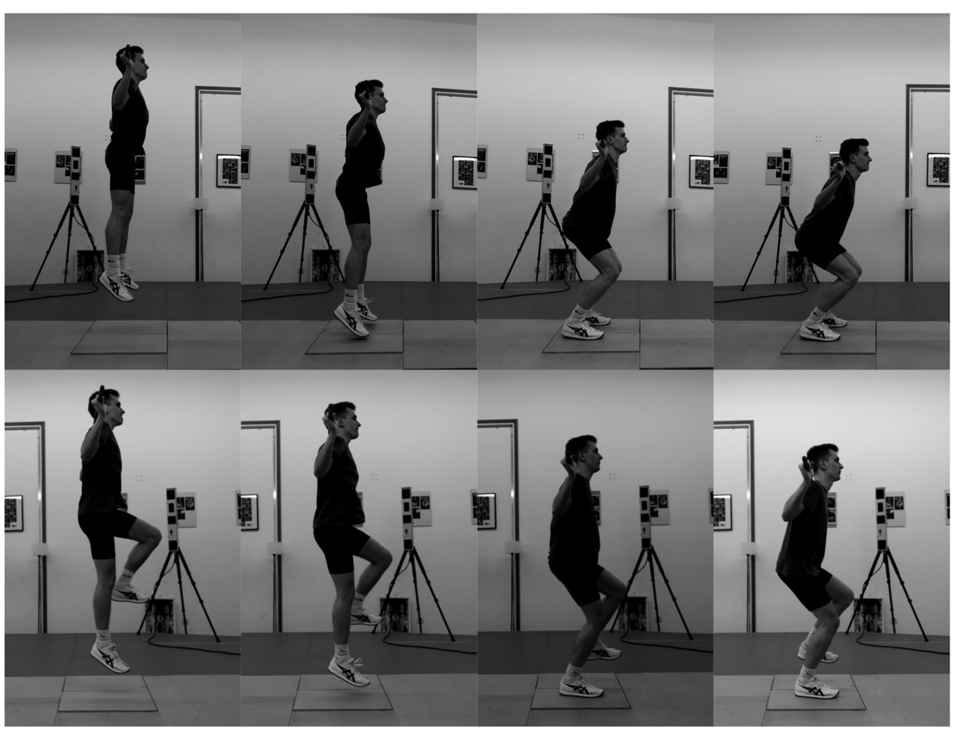

Figure 1. Examples of counter movement jump landings. Upper row: bipodal landing. Lower row: unipodal landing on the dominant leg.

exceeded 5% of the participant's body weight (Sheehan & Gottschall, 2012). The end of the landing phase was defined when the pelvis (modelled as the barycentre of the 4 superior iliac spines) achieved its lowest position.

This study focused on the variables directly obtained from the 3D measurements, namely angular positions, ground reaction forces and temporal variables. Other parameters, such as angular velocity and joint moments, derive from the previous parameters using biomechanical models and inverse dynamics and were not studied here. More precisely, hip, knee, and ankle joint angles were calculated for both the dominant and non-dominant side in the sagittal plane. The values of the joint angles were measured at impact (beginning of the landing phase) (Cortes et al., 2007; Decker, Torry, Wyland, Sterett, & Richard Steadman, 2003; Ford et al., 2007) and at the time of maximum ground reaction forces (Cortes et al., 2007). The amplitudes (peak-to-peak value) of joint displacement during the whole landing phase are also reported (Decker et al., 2003; Ford et al., 2007). Knee valgus was estimated as the lateral displacement of the knee in the frontal plane between the initial contact and the moment when maximal ground reaction forces occurred. Jump height was evaluated as the difference between the standing and maximal position of the pelvis.

Absolute reliability statistics (such as Standard Error of Measurements – SEM) are related to the variation of the value of a parameter, whereas relative reliability statistics (such as Intraclass Correlation Coefficient – ICC) are related to the variation of the rank of each individual (for the studied parameter) among the whole sample. ICC (and [95% confidence interval]), SEM, and Smallest Detectable Difference (SDD) were determined to assess the reliability of the biomechanical variables (Atkinson & Nevill, 1998; Bruton, Conway, & Holgate, 2000). Descriptive statistics (mean and standard deviation) were also provided. ICC was computed using the ICC (3, 1) formula. ICC values were interpreted as follows: ICC values less than 0.40, between 0.40 and 0.59, between 0.60 and 0.74, and larger than 0.75 reflect poor, moderate, good, and excellent reliability, respectively (Cicchetti, 1994). Contrary to the ICC, the SEM and SDD values are expressed in the same unit as the variables. It is the responsibility of the researcher to judge whether the values are small enough to be of practical use.

Results

The reliability of some common biomechanical variables (Onate, Cortes, Welch, & Van Lunen, 2010) is presented in Table I (bipodal jump), Table II (unipodal jump on the dominant side), and Table III (unipodal jump on the non-dominant side). Angular parameters are given at the time where the ground reaction forces are maximal. The reliability of the angular parameters at the time of impact as well as the reproducibility of their amplitude can be found in the supplementary files (S1, S2, and S3 for bipodal, dominant unipodal, and non-dominant unipodal, respectively).

ICC values concerning the vertical jump height were superior to 0.86 [0.6–1] for all tasks (unipodal, bipodal) and instruction conditions (with and without verbal instruction) (Tables I–III).

During the bipodal landings, when all the instants are considered (supplementary file S1), hip and knee angular positions had moderate to excellent ICC values (0.47 [0.0–0.8] to 0.97 [0.9–1.0]) and SEM inferior to 6.3° with and without instruction. The angular positions of the ankle had lower ICC values (0.67 [0.0–0.9] to 0.85 [0.5–1.0] without instruction and 0.46 [0.0–0.8] to 0.92 [0.7–1.0] with instruction). Similarly, SEM and SDD values were larger for the ankle, particularly at impact (supplementary files). As shown in Table I, temporal parameters (landing duration and time at maximum ground reaction forces) had excellent reliability indicators (ICC > 0.8 [0.4–0.9]), whereas concerning the ground reaction forces, SEM (251 to 394 N) and SDD (697 N to 1091 N) were large. With the verbal instruction, the reliability was improved for bipodal landings (ICC: 0.80, range 0.47–0.97 vs. 0.84, range 0.46–0.93) (supplementary file S4).

During unipodal landings, ICC values were close to those observed during bipodal landings. When all the instants are considered (supplementary files S2 and S3), hip and knee ICC values ranged from 0.20 [0.0–0.7] to 0.95 [0.8–1.0]. SEM and SSD for angular values were also, for most parameters, in the same range as during bipodal landing (SEM inferior to 5.9° and SDD inferior to 16.4°). The reliability at the ankle joint at impact (SEM < 9.5°, SDD < 25.8°) was again lower. The verbal instruction had, on average, a negative effect for unipodal landings (ICC on the dominant side: 0.75, range 0.20–0.97 vs. 0.68, range 0.38–0.86) (supplementary file S4).

The mean ICC of all the biomechanical parameters, computed either over all trials or on only the highest jump trial, were also compared (supplementary file S4). The results showed that reliability is better when all the trials are used to compute the biomechanical variables. For bipodal landings, the mean ICC was equal to 0.80 (range 0.47–0.97) against 0.69 (range 0.27–0.94) when only one trial was used. Similar results were obtained

Table I. Reliability of biomechanical variables during a bipodal counter movement jump landing phase (based on the mean of three trials)

	Descriptive statistics				Absolute reliability				Relative reliability			
	Mean ± std				SEM	SDD	SEM	SDD	ICC (3,1)	95% CI	ICC (3,1)	95% CI
	Without		With		Without		With		Without		With	
	Pre-test	Post-test	Pre-test	Post-test								
Height (m)	0.47 ± 0.06	0.45 ± 0.07	0.45 ± 0.1	0.44 ± 0.1	0.02	0.06	0.02	0.04	0.89	[0.5, 1.0]	0.93	[0.8, 1.0]
Hip at max force D (°)	43.9 ± 13.0	44.1 ± 15.4	43.3 ± 15.8	42.4 ± 14.5	4.9	13.6	4.4	12.2	0.88	[0.6, 1.0]	0.91	[0.7, 1.0]
Hip at max force ND (°)	44.8 ± 13.0	43.7 ± 15.2	45.5 ± 15.9	44.6 ± 14.9	4.1	11.2	3.9	10.9	0.91	[0.7, 1.0]	0.93	[0.8, 1.0]
Knee at max force D (°)	72.6 ± 15.5	68.7 ± 16.2	69.2 ± 11.9	68.1 ± 11.9	5.9	16.3	3.6	9.9	0.86	[0.6, 1.0]	0.91	[0.7, 1.0]
Knee at max force ND (°)	74.2 ± 15.5	69.7 ± 16.1	71.4 ± 11.7	70.5 ± 12.6	6.3	17.6	3.5	9.6	0.84	[0.5, 1.0]	0.92	[0.7, 1.0]
Knee valgus D (m)	0.001 ± 0.007	−0.003 ± 0.013	−0.003 ± 0.009	−0.003 ± 0.010	0.006	0.017	0.003	0.009	0.66	[0.2, 0.9]	0.88	[0.6, 1.0]
Knee valgus ND (m)	−0.002 ± 0.009	−0.006 ± 0.010	−0.005 ± 0.008	−0.008 ± 0.011	0.004	0.012	0.004	0.011	0.80	[0.3, 0.9]	0.82	[0.5, 0.9]
Ankle at max force D (°)	−27.1 ± 5.4	−24.8 ± 7.1	−26.1 ± 4.5	−25.1 ± 2.7	3.4	9.4	2.3	6.4	0.71	[0.3, 0.9]	0.61	[0.1, 0.9]
Ankle at max force ND (°)	−28.7 ± 5.3	−25.3 ± 5.9	−24.7 ± 5.7	−25.9 ± 4.1	3.3	9.1	3.6	9.9	0.67	[0.0, 0.9]	0.46	[−0.1, 0.8]
Force max D (N)	2146 ± 668	2423 ± 856	1838 ± 569	1788 ± 546	355	984	251	697	0.78	[0.4, 0.9]	0.79	[0.4, 0.9]
Force max ND (N)	2230 ± 624	2424 ± 964	2050 ± 540	1989 ± 512	394	1091	254	705	0.76	[0.4, 0.9]	0.76	[0.4, 0.9]
Landing duration (s)	0.201 ± 0.067	0.201 ± 0.075	0.205 ± 0.055	0.197 ± 0.051	0.031	0.086	0.013	0.037	0.80	[0.4, 0.9]	0.93	[0.8, 1.0]
Time to max force (s)	0.054 ± 0.016	0.053 ± 0.017	0.066 ± 0.017	0.065 ± 0.016	0.006	0.017	0.006	0.017	0.86	[0.6, 1.0]	0.85	[0.6, 1.0]

Notes: SEM: standard error of measurement; SDD: smallest detectable difference; ICC: intraclass correlation; CI: confidence interval; Without: without verbal instruction; With: with verbal instruction.

Table II. Reliability of biomechanical variables during a unipodal (dominant side) counter movement jump landing phase (based on the mean of three trials)

	Descriptive statistics				Absolute reliability				Relative reliability			
	Mean ± std											
	Without		With		SEM Without	SDD Without	SEM With	SDD With	ICC (3,1) Without	95% CI Without	ICC (3,1) With	95% CI With
	Pre-test	Post-test	Pre-test	Post-test								
Height (m)	0.29 ± 0.0	0.30 ± 0.05	0.29 ± 0.03	0.30 ± 0.04	0.01	0.03	0.01	0.04	0.93	[0.8, 1.0]	0.86	[0.6, 1.0]
Hip at max force D (°)	32.9 ± 10.8	35.7 ± 11.4	30.5 ± 7.2	32.9 ± 9.0	5.6	15.6	4.5	12.6	0.74	[0.3, 0.9]	0.68	[0.2, 0.9]
Knee at max force D (°)	58.2 ± 13.3	58.0 ± 10.8	54.4 ± 7.3	55.1 ± 7.3	4.5	12.6	4.2	11.8	0.85	[0.6, 1.0]	0.65	[0.1, 0.9]
Knee valgus D (m)	0.009 ± 0.008	0.006 ± 0.012	0.005 ± 0.008	0.005 ± 0.008	0.006	0.017	0.006	0.017	0.65	[0.2, 0.9]	0.38	[−0.3, 0.8]
Ankle at max force D (°)	−25.8 ± 5.6	−24.0 ± 6.3	−23.7 ± 3.9	−24.5 ± 4.4	3.0	8.3	2.4	6.6	0.74	[0.3, 0.9]	0.67	[0.2, 0.9]
Force max D (N)	2627 ± 554	2831 ± 453	2666 ± 372	2672 ± 347	193	534	161	446	0.85	[0.3, 1.0]	0.79	[0.4, 0.9]
Landing duration (s)	0.237 ± 0.080	0.236 ± 0.083	0.220 ± 0.047	0.244 ± 0.070	0.013	0.036	0.041	0.113	0.97	[0.9, 1.0]	0.53	[0.0, 0.8]
Time to max force (s)	0.068 ± 0.019	0.062 ± 0.022	0.072 ± 0.014	0.07 ± 0.018	0.011	0.031	0.007	0.020	0.70	[0.3, 0.9]	0.78	[0.4, 0.9]

Notes: SEM: standard error of measurement; SDD: smallest detectable difference; ICC: intraclass correlation; CI: confidence interval; Without: without verbal instruction; With: with verbal instruction.

Table III. Reliability of biomechanical variables during a unipodal (non-dominant) counter movement jump landing phase (based on the mean of three trials)

	Descriptive statistics				Absolute reliability				Relative reliability			
	Mean ± std											
	Without		With		SEM Without	SDD Without	SEM With	SDD With	ICC (3,1) Without	95% CI Without	ICC (3,1) With	95% CI With
	Pre-test	Post-test	Pre-test	Post-test								
Height (m)	0.30 ± 0.04	0.30 ± 0.04	0.28 ± 0.0	0.29 ± 0.0	0.01	0.03	0.01	0.04	0.93	[0.8, 1.0]	0.90	[0.7, 1.0]
Hip at max force ND (°)	36.0 ± 14.7	38.2 ± 15.3	33.7 ± 10.5	33.3 ± 13.0	3.6	10.1	4.2	11.5	0.94	[0.8, 1.0]	0.87	[0.6, 1.0]
Knee at max force ND (°)	59.0 ± 11.5	60.5 ± 11.6	57.1 ± 9.3	57.2 ± 11.9	4.2	11.5	3.3	9.1	0.86	[0.6, 1.0]	0.90	[0.7, 1.0]
Knee valgus ND (m)	0.002 ± 0.010	0.003 ± 0.016	0.001 ± 0.009	0.002 ± 0.008	0.005	0.015	0.004	0.011	0.84	[0.5, 1.0]	0.76	[0.4, 0.9]
Ankle at max force ND (°)	−25.3 ± 5.8	−24.3 ± 4.6	−25.4 ± 9.5	−23.7 ± 4.0	2.9	8.1	5.7	15.8	0.67	[0.2, 0.9]	0.37	[−0.2, 0.8]
Force max ND (N)	2679 ± 444	2793 ± 619	2493 ± 421	2628 ± 395	175	485	224	622	0.89	[0.7, 1.0]	0.69	[0.3, 0.9]
Landing duration (s)	0.235 ± 0.073	0.261 ± 0.109	0.225 ± 0.058	0.228 ± 0.056	0.035	0.096	0.022	0.061	0.85	[0.5, 1.0]	0.84	[0.5, 1.0]
Time to max force (s)	0.065 ± 0.025	0.067 ± 0.032	0.075 ± 0.014	0.07 ± 0.016	0.014	0.038	0.006	0.017	0.76	[0.3, 0.9]	0.83	[0.5, 1.0]

Notes: SEM: standard error of measurement; SDD: smallest detectable difference; ICC: intraclass correlation; CI: confidence interval; Without: without verbal instruction; With: with verbal instruction.

for all conditions (bipodal vs. unipodal landing, and with vs. without instruction).

Discussion

The aim of the present article was to evaluate the reliability of kinematic and kinetic variables during the landing phase for recreational athletes. Two specific factors were particularly investigated: the influence of unipodal versus bipodal landing, as well as the influence of a verbal instruction.

Both bipodal and unipodal jumping vertical height were found to be reliable. Similar results were reported by other authors for the counter movement jump (Moir, Shastri, & Connaboy, 2008), the block jump and the attack jump (Sattler, Sekulic, Hadzic, Uljevic, & Dervisevic, 2012). Concerning the landing patterns, most of the ICC values showed good to excellent reliability during the bipodal landing task. As in Milner et al. (2011) for a stop jump, lower reliability was obtained for the vertical ground reaction forces. For counter movement jumps, Cámara et al. (2011) found slightly higher and lower ICC values than in the present study for the vertical ground reaction forces (0.76–0.78 vs. 0.86) and time to peak force (0.85–0.86 vs. 0.77), respectively. However, Cámara et al. evaluated intra-session reproducibility rather than inter-session reproducibility as tested in our study. Despite the fact that landing on a single foot is more challenging in terms of balance due to a reduced base of support, the reliability of the landing was, overall, similar when performed as an unipodal task. Evaluating unipodal landing is interesting from a prevention of injury point of view as it could more easily lead to risky situations (Pappas et al., 2007). However, the ICC values, showing a relatively good reliability, should be mitigated by the SEM and SDD results for some variables. Relatively large values of SDD were found for both angular variables – mostly at the ankle joint at impact (up to 27.0°, which represents approximately 50% of the range of motion of the ankle during the landing) – and ground reaction forces (up to 1091 N, which also represents approximately 50% of the peak vertical ground reaction force). These values, which may not be acceptable from a practical point of view, show that the moment of impact is less reliable than the moment of peak vertical ground reaction force, which happens approximately 60 ms after the beginning of the landing phase. Evaluations of landing should, therefore, focus on the most reliable instant of landing (at peak ground reaction force). However, different results may be obtained with different landing procedures.

The reliability of the kinematic variables found in this study was slightly inferior to those reported in previous studies. ICCs over 0.9 and 0.8 were reported for drop jumps (Ford et al., 2007) and for stop jumps (Milner et al., 2011), respectively. Several reasons may explain these results. Firstly, the height for landing from a counter movement jump is approximately one third higher than the height usually used for drop jumps. Recreational athletes may have difficulties in dealing with the increased intensity of the landing. Laffaye et al. showed that there is an interaction between expertise and drop height on performance during a drop jump (30 vs. 60 cm) (Laffaye, Bardy, & Taiar, 2006). Secondly, for both the drop jump and the stop jump, the landing phase is an integral part of the required task. The athletes are, therefore, able to set up a mental representation of the motor task to come. The landing task may not be as well integrated during a counter movement jump as the landing phase comes after the specified goal (i.e. jump as high as possible) and may lead to less homogenous motor patterns. Bates et al. demonstrated that the second landing of a drop jump presents larger asymmetries concerning the side-to-side ground reaction forces and hypothesised that the second landing may better represent in-game mechanics (Bates, Ford, Myer, & Hewett, 2013). Thirdly, the restriction of arm mobility could also explain the reduced reliability.

The restriction of the arms may have reduced the ability of the participants to stabilise their trunk, and consequently their lower limbs (Willson, Dougherty, Ireland, & Davis, 2005), during the flight and landing phases of the jump. This methodological choice increased the importance of the trunk core stability capabilities of the participants on the final observed landing reliability. On the field, an inability to control the trunk may be due to core stability weaknesses but also to external perturbations. For instance, in basketball or volleyball the position of the trunk and the arms may be imposed by the trajectory of the ball or adjacent players. Yom et al. have shown that such in-flight perturbations lead to abnormal kinematics and ground reaction forces (Yom, Simpson, Arnett, & Brown, 2014). In Yom's study the lateral perturbation did not lead to kinematic variations at the ankle joint. In the present study; however, the antero-posterior instability of the trunk may have led to involuntary fore- or rear-foot landings. This hypothesis is corroborated by the large variability observed at the ankle joint and in particular at impact (during a fore-foot landing, the ankle is more plantar flexed than during a rear-foot landing). This behaviour is in opposition to an elaborated landing strategy as described in Cortes et al., where volunteers were asked to land with various foot-landing techniques (self-preferred, fore-foot, and rear-foot) (Cortes et al., 2007).

A novel aspect of the current study was to provide some volunteers with a verbal instruction. With the verbal instruction, our results for bipodal landings were improved. These results for bipodal landing demonstrate that an instruction, which is not explicitly focusing on the landing phase, can be an efficient approach to improve reliability when only one trial is used for the evaluation. The impact of the verbal instruction however was lower than consideration of several trials during the evaluation. Having a more specific instruction (Milner et al., 2012) such as "bend your knee" or "perform a soft landing" may have further improved the reliability of the test. However, in our opinion, such instructions may have modified the natural technique of the participants and the test would have no longer been representative of the field reality. Such instructions should be kept for postural/technical re-education programmes. In contrast to bipodal landing, the verbal instruction had globally negative effects for unipodal landings, especially on the non-dominant side for absolute reliability. The increased difficulty of landing on a single leg may have prevented the volunteers from taking advantage of the instruction. It has been demonstrated that during a dual-task test, the primary task performance can be impaired by a secondary (cognitive or motor) task (Ebersbach, Dimitrijevic, & Poewe, 1995). Based on these results, a hypothesis would be that the benefit on reliability of a verbal instruction would depend, among others, on the (motor) complexity of the primary task. More research is needed to confirm this hypothesis.

Within a population, the variability of measurements can be explained by three main causes: (1) the error of measurement, (2) the inter-subject variability (different morphology, motor strategies, etc.), and (3) the intra-subject variability (motoric noise) (Groot, 1997). The motoric noise is due to the kinematic variability of a subject and his inability to perform the same motion several times. Some reliability studies have shown that the variability is lower over a short period of time (within-session reliability) (Alenezi et al., 2014; Ditroilo, Forte, McKeown, Boreham, & De Vito, 2011). To limit the effect of the motoric noise, most studies (DiCesare et al., 2015; Ford et al., 2007; Milner et al., 2011; Padua et al., 2011) evaluated the reproducibility on the mean of several repetitions (between three and five). (Moir et al., 2008) did not find reliability differences concerning the jumping height when taking either the highest jump or the mean of three jumps. However, these results may not be valid for more complex variables (for instance biomechanical variables). We found that the results based on a single jump (highest jump) were, on average, less reliable. This approach has some limitations. Specifically, averaging several motions may lead to an underestimation of extreme amplitudes, which are part of the motor pattern of the athlete. These extreme amplitudes may be the cause of injuries on the field, and there could be a risk of underestimating the risk of injury. However, these considerations are beyond the scope of this study.

In the present study, the reliability of the parameters was only evaluated at specific key moments (0D analysis). Approaches based on the comparison of the whole kinematic/kinetic curves (1D analysis), such as statistical parametric mapping (Pataky, 2012; Pataky, Robinson, & Vanrenterghem, 2016), may have provided further insights concerning other parts of the motion. It should, however, be underlined that these methods usually request a time registration of the trials. It implies that specific events ("maximal ground reaction force", "maximal flexion", etc.) which have a clinical/biomechanical meaning, could no longer be extracted and studied. Finally, this study has only focused on a male population and our results may not have been the same in a female population. Indeed, gender differences exist in landing strategies (Decker et al., 2003). As the risk of ACL injuries is larger in women (Arendt, Agel, & Dick, 1999), a study similar to this one but focusing on women would be valuable to establish prevention tests.

Conclusion

Bipodal and unipodal landings after a counter movement jump present moderate to excellent reliability in a population of recreational athletes. However, as performed in this study (restricted arm motion), larger SEM were found at the ankle joints, especially at impact and concerning the ground reaction forces. It may not be possible to exploit these parameters in practice. Providing a verbal instruction improved the reproducibility of the bipodal landings and could be a valuable addition to an evaluation protocol. However, one should remain careful as the instruction had an opposite effect on unipodal landings (reduced reproducibility). This result may be related to the motor complexity of the unipodal landing condition.

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Supplementary data

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