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Differentiating Successful and Unsuccessful Single-Leg Drop Landing Performance Using Uncontrolled Manifold Analysis

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Abstract

Biomechanical analysis can effectively identify factors associated with task performance and injury risk, but often does not account for the interaction among the components that underlie task execution. Uncontrolled manifold (UCM) analyses were applied to data from 38 female, adolescent athletes performing single-leg drop landings and were used to differentiate successful and unsuccessful task performance by examining the frontal plane joint variance within the UCM (V_{UCM}) that stabilized the horizontal center of mass position (V_{UCM}) and within the orthogonal subspace (V_{ORT}). The UCM revealed stronger coordination, indicated by the $V_{\mathrm{UCM}}/V_{\mathrm{ORT}}$ ratio, in the successful condition. This may inform future research examining reduced motor coordination in failed movement tasks and its relation to injury risk and allow for targeted interventions that consider coordination processes rather than joint-specific outcomes.

Keywords

biomechanics; injury risk; coordination

Biomechanical analyses have classically been used to precisely quantify human movement and, more specifically, to identify mechanical factors, such as external forces and joint moments of force, which are known to influence wholebody and intersegmental movement patterns in the context of task performance, quality of movement, or injury risk. To that end, dynamic unilateral and bilateral tasks, such as the single-limb drop landing (Ali,

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Rouhi, & Robertson, 2013; Ford et al., 2006) and the drop vertical jump (Hewett et al., 2005; Myer et al., 2010), respectively, have been used to identify factors relating to both acute, secondary, and chronic injury. Specifically, the biomechanical measures associated with these tasks have been used to identify primary anterior cruciate ligament (ACL) risk (Ford et al., 2006; Hewett et al., 2005), secondary ACL injury risk (Paterno et al., 2010), and mechanisms of patellofemoral pain (Myer et al., 2010). The nature of these analyses (i.e., they are quantifiable, precise, and experimentally determined) has allowed researchers to uncover associations between certain biomechanical patterns and injury (i.e., external knee abduction moment and ACL injury; Hewett et al., 2005), and these have informed neuromuscular training interventions to improve outcomes (Hewett, Lindenfeld, Riccobene, & Noyes, 1999; Mandelbaum et al., 2005; Myer, Brent, Ford, & Hewett, 2008; Myer, Ford, Brent, & Hewett, 2007, 2012a, 2012b; Myer, Ford, McLean, & Hewett, 2006; Myer, Ford, Palumbo, & Hewett, 2005; Myer et al., 2013; Paterno et al., 2011). While important in this respect, such associations are not fully informative of the human movement system's organization and coordination and the way in which these system processes relate to task performance. This is because biomechanical analyses are limited to component-specific (e.g., joint-specific) assessments that, given the complexity and interconnectedness of the musculoskeletal system and its underlying neural control mechanisms, do not account for the interaction among components that underlie successful task execution. A more detailed understanding of the relevant coordination structures that occur among musculoskeletal degrees of freedom (DOF), or "synergies" (i.e., groups of DOF that are cohesively coupled to achieve and/or maintain a functional or behavioral goal; Riley, Kuznetsov, & Bonnette, 2011), which result in desired motor behavior, may provide more comprehensive insight into targeted injury risk improvement or performance enhancement interventions beyond the mechanical outcomes of movement. Specifically, this can allow for the characterization of finer scale processes that underlie the production of previously identified injury risk biomechanics and provide a window into the control processes that facilitate injury-resilient patterns of movement. Synergistic behavior has been quantified in the context of ACL injury risk (Paterno et al., 2015) and outcomes (Kiefer et al., 2013), which may subsequently inform the quantification of such behavior during tasks often used in biomechanical-based injury risk assessments.

One approach that quantifies synergistic behavior among motor system DOF is the uncontrolled manifold (UCM) analysis (Scholz & Schoner, 1999). The UCM analysis is based on the assumption that improved reciprocal compensation among system components underlies better coordinated movement (Riley et al., 2011), which is reflected in the stabilization of a performance variable (e.g., center of mass [COM] position) rather than the system's joint-specific movements, for example. This approach considers motor system DOF during task performance and constructs a subspace, or manifold, within a state space of task-relevant elements. The stabilization of the performance variable subsequently reflects coordination among DOF that are critical for executing a given task. Although UCM has been applied to functional tasks such as reaching (Reisman & Scholz, 2006; Yang, Scholz, & Latash, 2007), sit-to-stand (Greve, Zijlstra, Hortobagyi, & Bongers, 2013; Kuznetsov & Riley, 2012; Scholz & Schoner, 1999), multifinger force production (Scholz, Kang, Patterson, & Latash, 2003), and postural stability during quiet stance

(Krishnamoorthy, Yang, & Scholz, 2005), UCM has not been used to assess coordination in tasks traditionally utilized for biomechanical-based injury risk assessments. Moreover, to the authors' knowledge, UCM has not been used to differentiate successful versus unsuccessful task performance—an important gap in the literature—as the coordination of DOF during dynamic tasks has implications for reducing injury risk. For example, better optimized neuromuscular control during landing (Pollard, Sigward, & Powers, 2010) attenuates factors —particularly ground reaction force (Ali et al., 2013; Nyland, Burden, Krupp, & Caborn, 2011)—that instigate net moments applied to the lower extremities and have been associated with an increased risk for ACL injury (Hewett et al., 2005; Pollard et al., 2010).

In this investigation, a UCM analysis was applied to data from single-leg landing tasks— often used in the biomechanics literature to assess injury risk (Ali et al., 2013; Ford et al., 2006; Kipp, McLean, & Palmieri-Smith, 2011)—to examine the reciprocal compensation among musculoskeletal DOF (i.e., angular motion at the trunk, hip, knee, and ankle) to evaluate motor strategies associated with successful landings—during which the body's horizontal COM was stabilized over the stance limb without reliance on the opposite limb —and unsuccessful landings. Our hypothesis was twofold: (a) that more of the variance among the trunk and lower extremity joints during landing will stabilize the horizontal COM position in the successful condition and (b) that the UCM analysis would reveal stronger coordination among the trunk and lower extremity joints in the successful condition as opposed to the unsuccessful condition.

Methods

Participants

A total of 38 healthy, adolescent female soccer athletes (mean ± *SD*; age 16.0 ± 1.3 years; height 164.3 ± 5.1 cm; weight 61.4 ± 11.8 kg) were recruited from two local high schools to participate in a neuromuscular training study that included standard biomechanical testing (among other physiological and neuromuscular tests), during which subjects performed a series of dynamic tasks, including the single-leg drop landing (SLD; Figure 1a) and single-leg cross drop landing (SCD; Figure 1b). The study protocol was approved by the institutional review board before the start of the data collection, and informed written consent was obtained from each participant prior to biomechanical testing.

Apparatus

Three-dimensional motion capture data were collected using a high-speed, passive optical motion capture system (Motion Analysis Corp., Santa Rosa, CA) sampling at 240 Hz. The ground reaction force data were collected using two embedded force platforms (AMTI, Watertown, MA) at 1,200 Hz and were synchronized with the motion data. Each subject was instrumented with 37 retroreflective markers, with a minimum of three tracking markers on each segment (Figure 2). The markers were placed on the sternal notch and sacrum between the S5 and T1 vertebrae, and bilaterally on the acromioclavicular joint, lateral epicondyle of the elbow, mid-wrist, anterior superior iliac spine, greater trochanter, midthigh, medial and lateral femoral condyles, tibial tubercle, lateral and distal aspects of the shank, and medial and lateral malleoli. The participants also wore a standardized shoe (Supernova Glide

2; Adidas AG, Herzogenaurach, Germany) with markers embedded at the heel, the dorsal surface of the midfoot, the lateral foot (fifth metatarsal), and the central forefoot (between the second and third metatarsals).

Procedure

Before the dynamic trials were collected, a static trial was conducted with the participant in anatomical pose and with foot direction standardized to the laboratory's coordinate system. Each participant performed a minimum of three trials each of the SLD and SCD tasks on each side, respectively, with the limb order randomized. During the SLD tasks, the participants were first instructed to balance on top of a 31-cm box by aligning one foot with a piece of tape on the edge of the box and picking up the opposite foot. They were then instructed to drop forward off the box, land on the same foot, and hold the landing for a minimum of 2 s (Figure 1a). For the SCD task, the setup was similar to the SLD in that subjects first aligned one foot with a piece of tape on the edge of the box and picked up the opposite foot; however, when dropping off the box, the subject crossed the opposite foot in front of the balancing foot while hopping down and medially, ultimately landing on the opposite foot (Figure 1b).

In a classic biomechanical testing protocol, typically only successful trials (i.e., ones that meet a specified performance goal, such as a stable landing) are considered, and any trials that deviate from this goal are excluded. Participants were determined to have stabilized when their COM velocity fell below 0.1 m/s and remained there for at least 2 s. Unsuccessful trials were quantified as a failure by participants to minimize COM velocity during landing without either breaking contact with ground or relying on the opposite limb for support (Figure 3). Because of the nature of the testing protocol, unsuccessful trials were classified post hoc, that is, as they happened (and confirmed using the aforementioned quantification of stabilization). As a result, not all of the subjects had an unsuccessful trial for both the SLD and SCD tasks and thus, a subset of the original cohort of 38 subjects was used for both the SLD ($N = 28$) and SCD ($N = 26$) tasks, respectively; further, the landing foot was not controlled across the subjects; some of the subjects had unsuccessful landings on the left limb, whereas the others had unsuccessful landings on the right. However, the landing foot was controlled within subjects for every unsuccessful trial that was recorded, a successful trial was randomly chosen to be analyzed for the given subject, side, and task, such that an equal number of subjects and successful and unsuccessful trials were considered for the final analysis.

Data Processing

The marker trajectories were filtered using a low-pass, fourth-order Butterworth filter at a cutoff frequency of 12 Hz. A six-degrees-of-freedom skeletal model was applied to the marker trajectories to determine the position and orientation of each segment at each time sample; this model was scaled to the subject's height and weight, and its inertial parameters were modified according to gender (de Leva, 1996). Cardan joint angles of the trunk, hip, knee, and ankle, and the whole body COM were computed using Visual3D (C-Motion, Inc., Germantown, MD), and kinematic waveforms were exported using custom MATLAB software (The MathWorks Inc., Natick, MA) from the time of the initial contact, defined as the time at which the vertical ground reaction force exceeded 10 N, to 1,000 ms after the initial contact (i.e., 240 samples total). Additional details on the angle and COM calculation are provided in the Appendix.

UCM Analysis

A single-trial UCM analysis was used in this study to investigate whether increased reciprocal compensation among the trunk, hip, knee, and ankle in the frontal plane resulted in the stabilization of the COM position in the mediolateral direction (COM_{ML}) upon landing. For each subject, task (SLD and SCD) and condition (successful and unsuccessful), a different UCM was calculated. In brief, a model relating the changes in COM_{ML} to the variability in ankle, knee, hip, and trunk angle was computed, and a linear approximation to each UCM was calculated from the null space of the Jacobian matrix of the model at a reference joint configuration (designated as the average joint configuration over stance). The magnitudes of the joint variances that left the COM_{ML} position unchanged (V_{UCM}), that is, the deviations that occurred along or within the UCM and that led to changes in the COM_{ML} position (V_{ORT}), that is, deviations that moved away from the UCM, were computed and normalized to their respective subspaces (i.e., the parallel and perpendicular projections, respectively). Additional details on the UCM analysis are provided in the Appendix.

The V_{UCM} and V_{ORT} values were log normalized to control for positive skew. The ratio of these outputs (V_{UCM}/V_{ORT}) was considered for each manifold and aggregated across subjects, conditions, and directions. A ratio >1 indicated that the hypothesis should be accepted (i.e., the COM position is a controlled task variable), as well as the extent to which the COM position was controlled via the relation among the joints. In addition, an index of motor abundance (IMA) was computed (Fietzer, Winstein, & Kulig, 2018) using the following equation:

$$\mathrm{IMA} = \frac{V_{UCM} - V_{ORT}}{V_{UCM} + V_{ORT}}$$

Statistical Analysis

The average V_{UCM} and V_{ORT} values were submitted to two separate 2 × 2 (Condition × Source of variance) repeated-measures generalized linear models for each landing task, respectively, to test the hypothesis that more of the trunk and lower extremity joint variance would lie within the UCM as opposed to the orthogonal subspace in the successful condition. Subsequently, paired *t* tests were used to assess the differences in the ratio of these outputs (V_{UCM}/V_{ORT}), as well as the computed IMA, to test the hypothesis that stronger trunk and lower extremity coordination would be evident in the successful condition as compared with the unsuccessful condition. An alpha level of .05 was selected a priori to assess significance, and an alpha level of .10 was used to signify a nonsignificant trend.

Results

Figure 4 illustrates the summary statistics for the UCM analysis, grouped by task (SLD vs. SCD), condition (i.e., successful vs. unsuccessful), and source of variance (i.e., V_{UCM} vs.

V_{ORT}). There was a significant main effect of source of variance for both the SLD task, $F(1, 27) = 9.88$, $p = .002$, and SCD task, $F(1, 25) = 12.85$, $p < .001$, indicating that V_{UCM} was greater than V_{ORT} and that the mediolateral position of the COM was controlled by the synergistic coordination of the lower limb (i.e., the coordination among the trunk, hip, knee, and ankle joints). There was also a significant main effect of condition for both the SLD task, $F(1, 27) = 11.56$, $p < .001$, and SCD task, $F(1, 25) = 30.76$, $p < .001$. There were no significant main effects of Condition × Source for either task; however, for the SLD task, there was a trend toward significance ($p = .058$).

The V_{UCM}/V_{ORT} ratio was significantly higher during the SCD task in the successful condition versus the unsuccessful condition ($p = .045$; Figure 4), while the ratio showed a trend toward significance for the SLD task ($p = .072$; Figure 4). Conversely, the IMA was significantly higher in the successful condition versus unsuccessful condition for the SLD task (IMA = 0.205 vs. 0.060, $p = .014$), while the IMA showed a trend for the SCD task (IMA = 0.182 vs. 0.068, $p = .070$).

Discussion

In this study, a single-trial UCM approach was applied to examine the variance in trunk, hip, knee, and ankle joint configuration in the frontal plane exhibited during two single-leg landing tasks of varying difficulty that resulted in the control of the performance variable, COM_{ML}, in both successful and unsuccessful landing performance. We expected that more of the joint variance during landing would lie within the UCM as opposed to the orthogonal subspace during the successful condition. In addition, we expected that, in the successful condition, stronger coordination of the lower extremity joints would be revealed through the UCM approach. Regarding the former, the interaction between the condition (successful vs. unsuccessful) and source of variance (i.e., V_{UCM} vs. V_{ORT}), while not significant, showed a likely association between the joint variance that stabilizes the COM_{ML} position and the success of a dynamic single-leg landing. Subsequently, the UCM analysis revealed either a significantly greater or a nonsignificant trend of stronger coordination during both the SLD and SCD tasks, as indicated by an increased V_{UCM}/V_{ORT} ratio and IMA measures in the successful condition as compared with the unsuccessful condition.

The execution of a specified movement task requires the successful coordination of multiple musculoskeletal DOF, the number of which generally exceeds the constraints associated with a given action and is ultimately reduced to stabilize task performance (Bernstein, 1967). Because of this redundancy, or perhaps more accurately, abundance (Latash, 2000), at the neuromuscular level compared with the kinematic level, the neuromuscular system is highly adaptable in the coordination it is able to achieve with available DOF. Subsequently, the structural units that are organized to achieve a given task exhibit reciprocity and compensation and can execute the task by many potential means; systems that abide by this are synergistic (Latash, Scholz, & Schoner, 2002). This is especially important for dynamic movements in sport, especially single-leg landings, in which synergistic behavior among the motor system DOF are responsible for safe, effective movement patterns that may protect against injury (Kipp et al., 2011), particularly in female athletes (Ali et al., 2013; Ford et al., 2006). For single-leg landing tasks, the stabilization of the COM position in the mediolateral direction is especially critical, given the relatively small base of support of the horizontal foot, and a lack of effective control can lead to a loss of balance as the COM_{ML} approaches the support boundary. For example, the variability of the center of pressure of the stance foot in the mediolateral plane, which reflects the neuromuscular response in keeping the COM_{ML} over the base of support (Winter, Prince, Frank, Powell, & Zabjek, 1996), has been associated with fall occurrence in older adults (Swanenburg, de Bruin, Uebelhart, & Mulder, 2010). Thus, COM_{ML} is a pertinent control variable during dynamic single-leg stabilization tasks.

During performance of both the SLD and SCD tasks, variability in joint configuration led to control of the COM_{ML} in both conditions, as indicated by the mean V_{UCM}/V_{ORT} ratios >1. Specifically, the UCM analysis revealed that variance in the trunk and lower extremity joint configuration stabilized the COM_{ML} position during these tasks, suggesting that synergistic and compensatory control of these joints was evident during landing. That COM_{ML} was controlled in both the successful and unsuccessful conditions is likely indicative of normal and comparatively similar motor coordination patterns, in which this group—healthy, active, athletes—is reasonably assumed to exhibit. However, coordination tended to be stronger in the successful condition (as evidenced by a nonsignificant trend toward an increased V_{UCM}/V_{ORT} ratio and significant increase in IMA in the SLD task, and vice versa in the SCD task) as opposed to the unsuccessful condition. Thus, although a significant Condition × Source interaction was not observed for either the SLD or the SCD task, that coordination tended to be stronger in the successful condition indicated that the synergistic behavior of the motor system DOF involved in the stabilization of the COM_{ML} position during landing was different (and improved) in the successful condition. Subsequently, that similar patterns were observed over two similar single-leg landing tasks signifies the robustness of this approach.

These findings have the potential to inform researchers who want to design more targeted approaches to biomechanical analysis to better understand an individual’s risk for musculoskeletal injury and to identify targeted interventions to address deficits in coordination control. Unlike classic biomechanical outcomes that provide a one-dimensional outcome variable (e.g., knee abduction) to target for a given intervention, the UCM results provide a more robust profile of coordination that objectively quantifies the synergistic coordination that manifests for the individual to produce a given outcome. These synergies are made up of muscular articular linkages that communicate (or are stimulated) via mechanoreceptors in the muscles, tendons, and skin, which are principally involved in proprioception (i.e., the perception of segmental inertial properties; Kugler & Turvey, 2015). Thus, that synergies were weaker in the unsuccessful condition, as quantified via the V_{UCM}/V_{ORT} ratio and IMA metrics, indicates the “connectedness” of the system. In the context of different performance environments (and associated task goals), these ratios may provide information about the context-specific adaptability of an individual. That is, the synergistic coordination for different modes of behavior and at higher levels of control may lead to more a successful performance (Klous, Mikulic, & Latash, 2011; Riley et al., 2011). Future research will be best served to examine the change of these coordination patterns as task difficulty is increased and, across a variety of sport-specific tasks, to build a more complete understanding of the role synergistic coordination plays in performance variables associated with injury risk mechanisms.

A limitation in this study was related to the single-trial UCM approach used; although we considered the entire cohort for each task, the lack of multiple trials for each participant in each condition prevented the use of a traditional UCM approach to analyze intertrial variance. In addition, as we combined data across both limbs to account for a higher number of unsuccessful trials collected post hoc, not all interlimb differences (e.g., dominant vs. nondominant) were assessed, which perhaps confounded the results. More trials are needed to assess not only interlimb coordination, but also intertrial coordination and interparticipant coordination. Another limitation was that we only considered a single time period (i.e., 1-s period following the initial contact with the force platform). This study may have benefitted from an analysis of other, disjoint time periods, including analysis windows before and after the 1-s window examined in this study. Specifically, the current data could be split into time periods and analyzed to see at what times before landing (e.g., the time prior to the jump, the initial jump, and movements during the jump), coordinative behavior may differ between successful and unsuccessful trials. This approach can potentially pinpoint the exact movement phases where coordinative patterns fail (functionally) and may allow targeted interventions to change behavioral patterns during that period. Another limitation relates to the selection of DOF for the model (i.e., stance limb ankle, knee, hip, and trunk); the DOF were selected as a means of simplifying the model's complexity, and we acknowledge the influence that the arms and nonstance limb likely have in stabilizing the COM during single-leg landing tasks. Future work should include these DOF in the model or control for their movement, such as by having the individuals fold their arms across their chest while landing, which would isolate the landing strategy to just that of the lower extremities and the trunk/head. Finally, this study used all female, adolescent athletes; this particular group presents a number of limitations, in particular, the potential for intergender differences and the potential confounding effect of being trained for athletic performance, given that they were reasonably high-level athletes. Future work can and should assess the effects of athletic participation, training status (e.g., novice vs. athlete), and performance on coordination during various landing and jumping tasks.

Conclusion

The UCM approach applied in this study extends classical biomechanical analysis by considering coordination strategies in all potential outcomes of task performance, including both successful and failed attempts of movement tasks. To that end, the participants exhibited decreased coordination during unsuccessful single-leg landings, whereas during the successful landings, an increased coordination was observed that attenuated the control variable (COM_{ML}). Future investigations should focus on how reduced motor coordination as observed in failed movement tasks relates to injury risk factors, as well as the potential effects of training, athletic performance, and rehabilitation on coordination processes. This will ultimately allow for targeted interventions that consider motor control processes, rather than joint-specific outcomes, for movement assessment.

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Appendix

Calculation and Processing of Joint Angles and COM

An x-y-z Cardan rotation sequence was used to compute the relative angles between the body segments. For the hip, knee, and ankle joints, angular position was calculated as the position of the segment distal to the joint relative to the proximal segment (e.g., hip joint angle was computed as the position of the thigh segment relative to the pelvis). The trunk angle was calculated as the position of the trunk segment relative to the global laboratory coordinate system. The COM of the model was determined using an estimate of the locations of each segment COM (foot × 2, shank × 2, thigh × 2, pelvis, trunk, upper arm × 2, and forearm × 2) and inertial parameters (de Leva, 1996) according to the following relation:

$$\mathrm{COM} = \frac{\sum_{i=1}^{12} m_i r_i}{M}$$

where m_i is the mass of the ith segment, r_i are the three-dimensional coordinates, and M is the total body mass.

UCM Analysis

The goal of the UCM approach applied in the present study was to quantify the amount of variability of the trunk, hip, knee, and ankle joint angular motion that falls within the UCM (as opposed to orthogonal to it) in both successful and unsuccessful SLD and SCD landing performance. To quantify these, we used a modified four-segment link model of the postural kinematic chain (Hsu, Scholz, Schoner, Jeka, & Kiemel, 2007; Kuznetsov & Riley, 2012) to relate the changes in the joint angles to the position of the $\mathrm{COM_{ML}}$:

$$\begin{aligned}
\mathrm{COM_{ML}} = \{ & m_{\mathrm{shank}} \times [d_{\mathrm{shank}} \times l_{\mathrm{shank}} \times \cos(180 - \Theta_{\mathrm{ankle}})] \\
& + m_{\mathrm{thigh}} \times [l_{\mathrm{shank}} \times \cos(180 - \Theta_{\mathrm{ankle}}) + d_{\mathrm{thigh}} \times l_{\mathrm{thigh}} \times \cos(180 - \Theta_{\mathrm{ankle}} + \Theta_{\mathrm{knee}})] \\
& + m_{\mathrm{pelvis}} \times [l_{\mathrm{shank}} \times \cos(180 - \Theta_{\mathrm{ankle}}) + l_{\mathrm{thigh}} \times \cos(180 - \Theta_{\mathrm{ankle}} + \Theta_{\mathrm{knee}}) \\
& + d_{\mathrm{pelvis}} \times l_{\mathrm{pelvis}} \times \cos(180 - \Theta_{\mathrm{ankle}} + \Theta_{\mathrm{knee}} + \Theta_{\mathrm{hip}})] \\
& + m_{\mathrm{trunk}} \times [l_{\mathrm{shank}} \times \cos(180 - \Theta_{\mathrm{ankle}}) + l_{\mathrm{thigh}} \times \cos(180 - \Theta_{\mathrm{ankle}} + \Theta_{\mathrm{knee}}) \\
& + l_{\mathrm{pelvis}} \times \cos(180 - \Theta_{\mathrm{ankle}} + \Theta_{\mathrm{knee}} + \Theta_{\mathrm{hip}}) \\
& + d_{\mathrm{trunk}} \times l_{\mathrm{trunk}} \times \cos(180 - \Theta_{\mathrm{ankle}} + \Theta_{\mathrm{knee}} + \Theta_{\mathrm{hip}} + \Theta_{\mathrm{trunk}})]\} \; / \; \mathrm{mass},
\end{aligned}$$

where $m_{\mathrm{shank}}, \cdots m_{\mathrm{trunk}}$ are the masses of the respective segments, $d_{\mathrm{shank}}, \cdots d_{\mathrm{trunk}}$ are the estimated locations of the COM of each segment as a proportion from the distal end (Winter, 2009), $l_{\mathrm{shank}}, \ldots l_{\mathrm{trunk}}$ are the lengths of the respective segments, $\Theta_{\mathrm{ankle}}, \cdots \Theta_{\mathrm{trunk}}$ are the joint angles in degrees, and mass is the total body mass (i.e., the sum of the masses of all segments). Thus, combinations of the four-dimensional joint space that keep $\mathrm{COM_{ML}}$ unchanged define the three-dimensional UCM. It was assumed, similarly to Hsu et al. (2007) and Kuznetsov et al. (2012), that the point that specifies the UCM during landing is defined by the average $\mathrm{COM_{ML}}$ position over the landing period (defined as 1 s in this study) and was the joint configuration around which the $\mathrm{COM_{ML}}$ was stabilized; thus, the average

$\mathrm{COM}_{\mathrm{ML}}$ position over landing represented the reference joint configuration ($\bar{\theta}$) for a given trial.

For each UCM, a linear approximation (e) was calculated from the null space of the Jacobian matrix of the model at the reference joint configuration. To determine the null space, MATLAB's *null* function with an orthonormal basis was used. Then, the reference joint configuration $\bar{\theta}$ was subtracted from the joint configuration at each sample during each trial and then projected into the basis vector spanning the linearized UCM:

$$\mathrm{UCM} = \sum_{i=1}^{n-d} \frac{(\theta - \bar{\theta}) \cdot e_i}{e_i \cdot e_i},$$

and the orthogonal projection:

$$\mathrm{ORT} = (\theta - \bar{\theta}) - \mathrm{UCM},$$

where (·) denotes the dot product between vectors, n is the number of joints ($n = 4$), and d is the number of control variables ($d = 1$).

Subsequently, the magnitudes of the joint variances that leave the $\mathrm{COM}_{\mathrm{ML}}$ position unchanged (V_{UCM}) and that lead to changes in the $\mathrm{COM}_{\mathrm{ML}}$ position (V_{ORT}) were calculated as:

$$V_{\mathrm{UCM}} = \frac{\sum_{i=1}^{N} (\mathrm{UCM}_i \cdot \mathrm{UCM}_i)}{N \times (n - d)},$$

and

$$V_{\mathrm{ORT}} = \frac{\sum_{i=1}^{N} (\mathrm{ORT}_i \cdot \mathrm{ORT}_i)}{N \times d},$$

where $N = 240$ is the number of samples per trial, $n = 4$, and $d = 1$. See Kuznetsov and Riley (2012) for additional details on these calculations.

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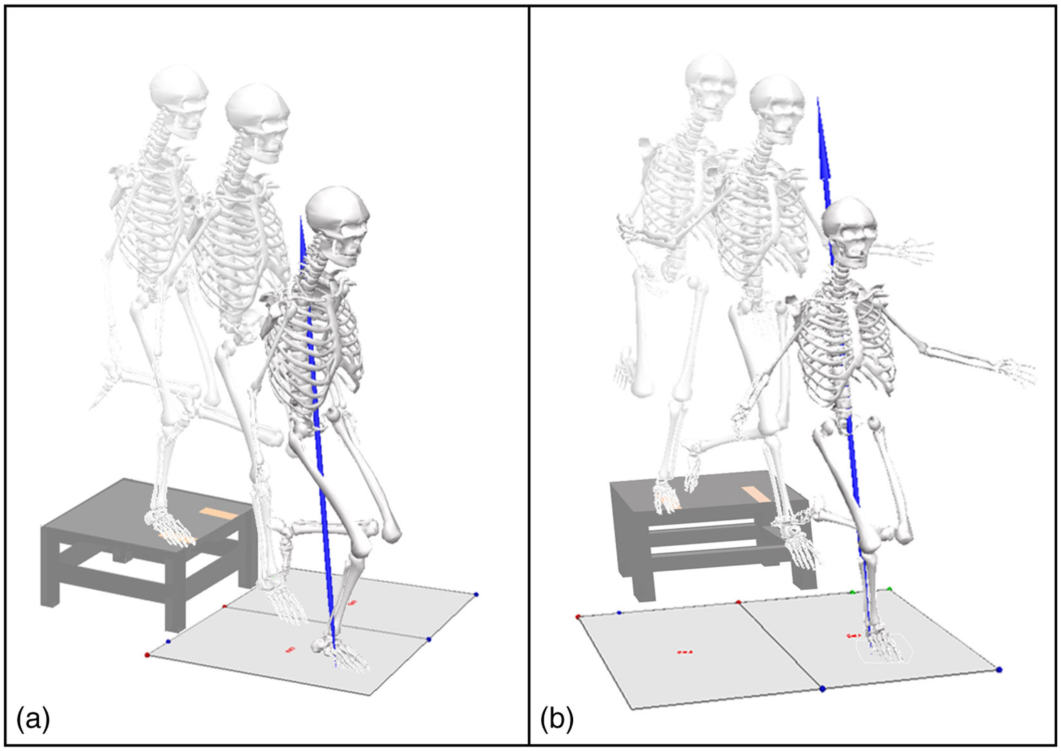

Figure 1 —.

Illustration of both the SLD (left) and SCD (right) task execution. During the SLD, the subject left the box and landed on the same limb, as opposed to the SCD, during which the subject would leave the box and land using opposite limbs. *Note*. SLD = single-leg drop landing; SCD = single-leg cross drop landing.

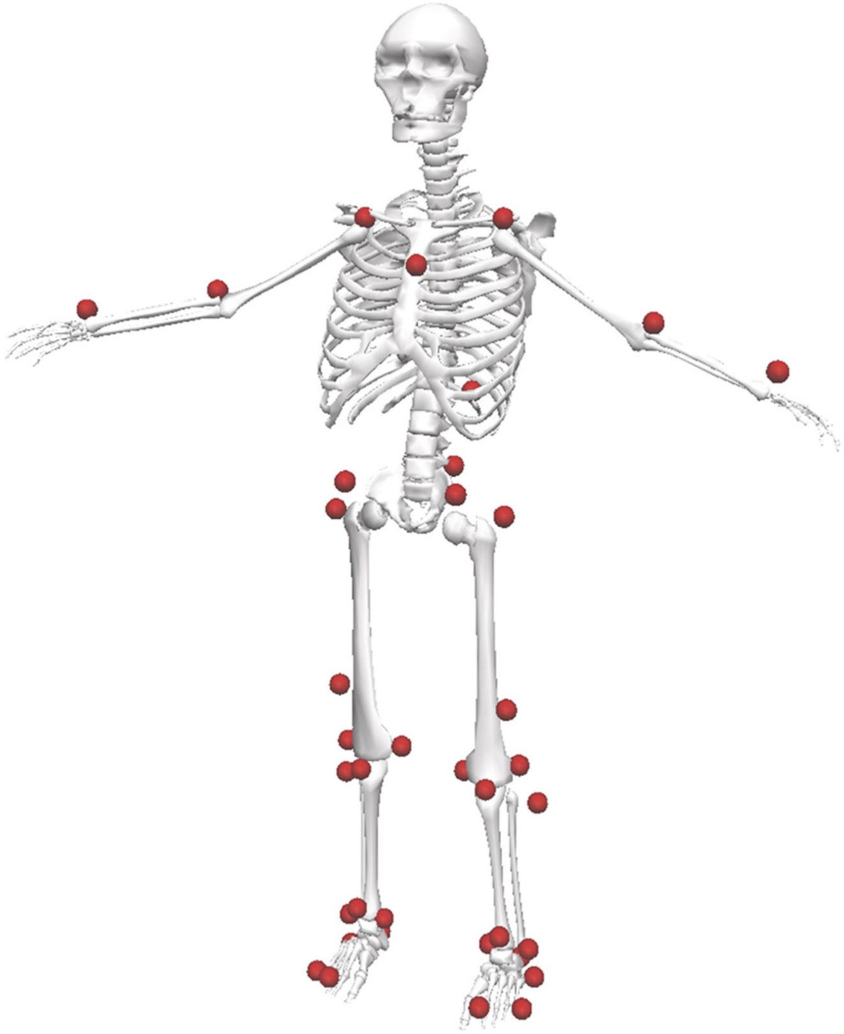

Figure 2 —.

Marker placement and resultant skeletal model for a representative subject in anatomical pose.

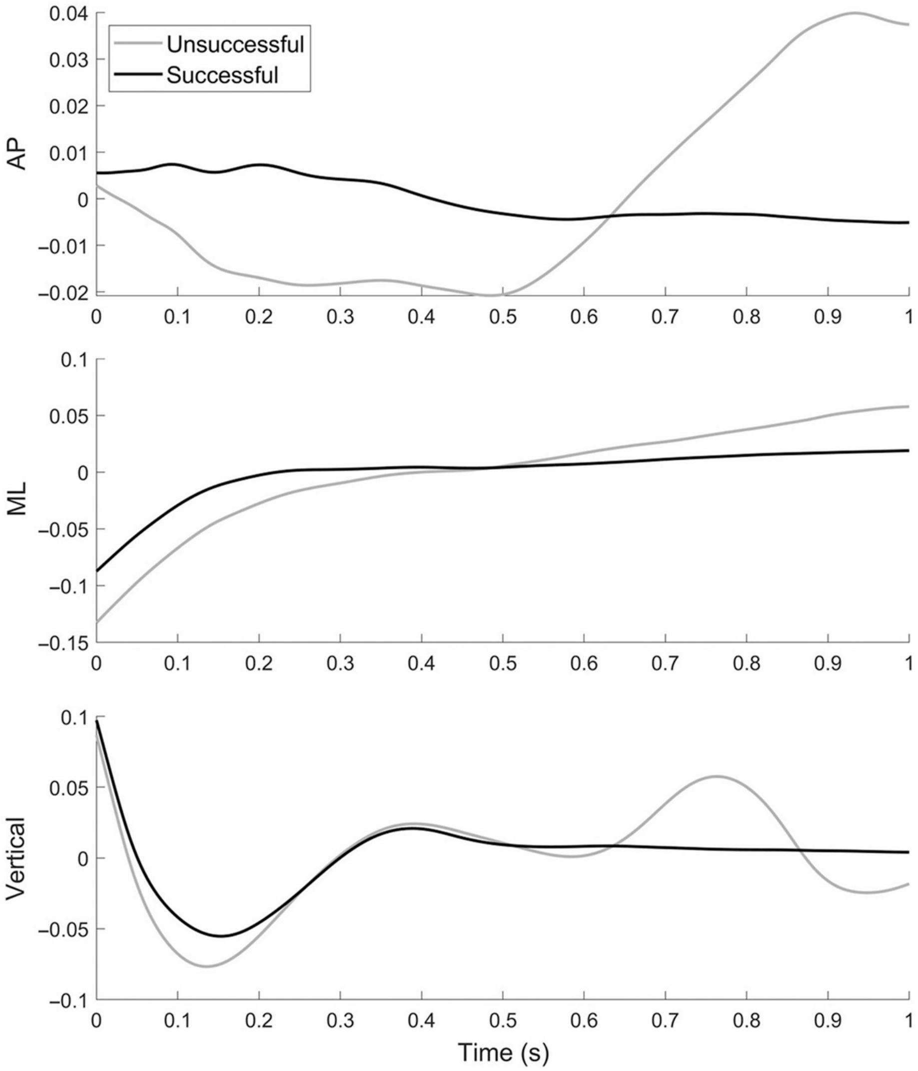

Figure 3 —.

The normalized body COM trajectories in the AP (top), ML (center), and vertical (bottom) directions for both successful (black) and unsuccessful single-leg landing performance (gray) by a representative subject during landing (the 1-s time period following the initial contact). *Note.* COM = center of mass; AP = anteroposterior; ML = mediolateral.

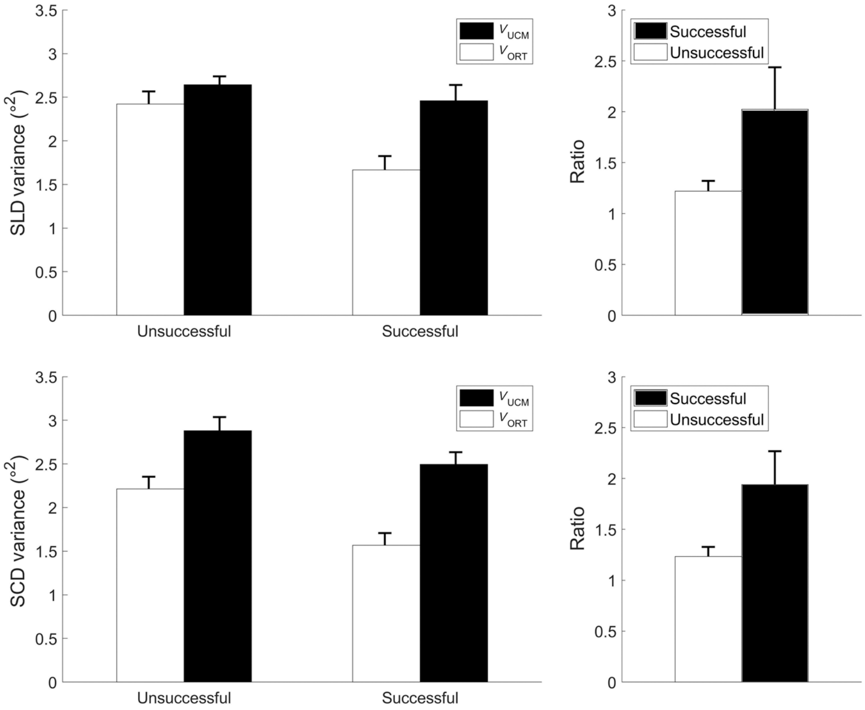

Figure 4 —.

Left: Summaries of the log-normalized V_{UCM} and V_{ORT} values (°2) during landing (the 1-s time period following the initial contact) across both the conditions and tasks (SLD, top; SCD, bottom). Right: The V_{UCM}/V_{ORT} ratios for both the conditions and tasks. *Note.* SLD = single-leg drop landing; SCD = single-leg cross drop landing; V_{UCM} = variance within uncontrolled manifold; V_{ORT} = variance within the orthogonal subspace.