Reliability of Ground Reaction Force Measurements During Dynamic Transitions from Bipedal to Single-Limb Stance in Healthy Adults

The consistency of ground reaction force (GRF) variables underlying dynamic transitions from bipedal to single-limb stance during a single-leg flexion movement was examined in 18 healthy adult subjects aged 21 to 47 years ($X=31.1, SD=8.6$). Force platforms were used to measure the GRFs during fast and natural speeds of movement. Separate intraclass correlation coefficients (ICCs) were calculated for three temporal variables (ie, onset of the propulsive and braking phases of the lateral horizontal GRF component and time to unload the flexing limb) and for two magnitude variables (ie, propulsive impulse [PROP] and braking impulse [BRAK]). The ICCs for both PROP and BRAK were $\geq 73$ for fast movements and $\geq 88$ at the natural speed. The ICCs for the temporal variables were $\geq 66$ at fast speeds and $\geq 37$ at the natural speed. We concluded that measurements of PROP and BRAK are reliable across a range of speeds during transitions in stance support and that these variables may be tightly regulated by the movement control system. Temporal variables, particularly at the natural speed, exhibited lower reliability estimates, suggesting that measurements of these events have greater variability. Reliability of measurements of GRF variables provides useful information for the clinician regarding underlying control processes governing dynamic transitions in stance support. [Hanke TA, Rogers MW. Reliability of ground reaction force measurements during dynamic transitions from bipedal to single-limb stance in healthy adults. Phys Ther. 1992;72:810–816.]

Key Words: Assessment, Balance, Ground reaction forces, Human stance, Movement, Reliability.

Physical therapists routinely measure the movement performance of their patients and plan treatment protocols must be justified with respect to reliability and validity so as to provide accurate information and to minimize misleading interpretations. Subsequently, treatment protocols based on invalid or unreliable measurements may not adequately address underlying dysfunction and thus diminish therapeutic effectiveness.

Evaluation of Balance and Posture

Accurate and repeatable measurement of standing balance and posture is important for physical therapists working with patients with a variety of diagnoses involving the neuromuscu-
The assessment of an individual's ability to maintain quasi-static balance while standing on one limb is commonly used for persons who have sustained a cerebrovascular accident and for patients following orthopedic injuries such as lateral ankle sprains. Similarly, single-limb stance has been used to screen older adult populations for the potential for falls and during the preseason screening process of athletes. Assessment of single-limb stance is usually accomplished by timing how long the posture is maintained and by making qualitative observations as to the amount of instability or sway the patient demonstrates when on an involved or uninvolved limb. Maintenance of such a quasi-static posture, however, may not reflect the individual's ability to perform the necessary dynamic weight transfer function when moving from bipedal to single-limb stance support.

The ability to actively shift the body CM laterally while standing is a prerequisite to the removal of the lower limb from the ground, as occurs with single-leg flexion, and for the initiation and ongoing execution of human gait. Examination of the ground reaction forces (GRFs) acting on the body during a standing leg flexion task has provided insight into the processes underlying the control of motion of the body CM. These kinetic events (Figure) are reflected in the resultant lateral horizontal (Fy) component of the GRF (ie, the summation of the separate lateral horizontal GRF components beneath each limb) in the frontal plane. For example, the onset of linear movement of the body CM laterally toward the upcoming single stance limb is determined by the earliest change in the baseline of the resultant Fy GRF (line A in the Figure). Similarly, the onset of unloading of the flexing limb (line B in the Figure) is indicated by a continuous reduction in the vertical (Fz) GRF component beneath the flexing limb. This reduction follows an initial increase in force at faster movement.

**Transitions in Stance Support**

The assessment of an individual's ability to maintain quasi-static balance while standing on one limb is commonly used for persons who have sustained a cerebrovascular accident and for patients following orthopedic injuries such as lateral ankle sprains. Similarly, single-limb stance has been used to screen older adult populations for the potential for falls and during the preseason screening process of athletes. Assessment of single-limb stance is usually accomplished by timing how long the posture is maintained and by making qualitative observations as to the amount of instability or sway the patient demonstrates when on an involved or uninvolved limb. Maintenance of such a quasi-static posture, however, may not reflect the individual's ability to perform the necessary dynamic weight transfer function when moving from bipedal to single-limb stance support.

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speeds. This early increase in vertical force prior to unloading of the flexing limb probably contributes to rotating the body laterally and to moving the limb from the ground.\(^2\) Furthermore, the interval between the onset of unloading and the point at which the flexing limb has left the support surface at \(F_z\) equal to zero (line \(B\) to line \(D\) in the Figure) indicates the total time to unload the flexing limb.

Findings pertaining to the resultant \(F_y\) GRF component have revealed additional details of lateral weight transfer function during standing single-leg flexion. For example, a propulsive impulse (PROP) (ie, the net effect of force acting over a period of time, shown as line \(A\) to line \(C\) in the Figure) in the horizontal direction prior to lift-off is required to generate sufficient linear momentum (ie, the product of body mass and velocity) of the CM during transitions from bipedal to single-limb support. The PROP must then reverse direction to become a braking impulse (BRAK) (line \(C\) to line \(E\) in the Figure) in order to slow the body momentum.\(^1\) Without this slowed momentum, disequilibrium in the frontal plane would likely occur. Thus, the resultant sum of the GRFs in the frontal plane beneath each lower limb would determine the profile of the horizontal linear momentum of the CM.\(^1\) Consequentially, the timing and magnitude of the PROP and BRAK should be critically related to overcoming the inertia of the body mass and to the dynamic processes of stance alteration and balance control.

In healthy young adults performing a standing single-leg flexion movement, an active increase in the resultant horizontal force has been found to precede the onset of unloading of the flexing limb and is directly responsible for the linear displacement of the CM toward the upcoming single stance limb.\(^2\) Moreover, both the normalized timing of the onset of braking and the magnitudes of PROP and BRAK remained unchanged for significantly different speeds of voluntary leg flexion.\(^3\) Thus, the control of linear motion of the total body laterally would appear to be an invariant feature of the intended act of withdrawing a lower limb from the ground while standing within a range of rapid to natural self-selected speeds of movement.

A determination of the reliability of the measurements of key kinetic events during the transition from bipedal to single-limb stance is needed in order to effectively utilize this task as an assessment tool. Rothstein\(^1\) has summarized three sources of error that may contribute to unreliable measurements: (1) instrumentation error, (2) inconsistency in the variable of the task that the subject is performing, and (3) evaluator error. Qualitative observations and functional scales used to assess standing single-leg flexion are likely dependent on the evaluator's experience and assumptions. These variables may potentially increase the variability of the measurement tool among different evaluators. Furthermore, such measurement tools generally lack the ability to elucidate the dynamics of lateral weight transfer from bipedal to single-limb stance.

An inherent lack of consistency in the measured variable (eg, time to unload the flexing limb) may be influenced by differing initial postures as well as variations in self-selected movement speed. In order to minimize the effects of such factors on the variability of the outcome measures, we have standardized the position of the upper limbs and feet without constraining the location of the body CM while making repeated measurements across natural and fast speeds of movement. Although standardization of initial conditions may challenge the generalizability of the measured outcome to more natural behavior, failure to consider such factors may increase the variability of performance measures and confound interpretation of the data.

Finally, evaluator error may play a significant role during the evaluation of standing balance using the single-limb stance task, particularly when measurements rely on qualitative observations. Potential error using the instrumentation described in this report may include determination of when GRF events begin and end. Graphical analysis programs that assist in this endeavor may minimize such error. Such instrumentation (eg, force platform) is becoming increasingly important in studying human motor behavior and has become available to the physical therapist in various forms.

When estimating the reliability of a measurement, the population in which the task is used is of considerable importance.\(^1\) Establishment of the reliability of measurements of the kinetic variables underlying dynamic transitions from bipedal to single-limb stance within a healthy adult population is needed in order to gather reference information and to enhance the ability of clinicians to make valid inferences regarding weight transfer function. Furthermore, in order to understand how these kinetic events may be altered in patients with disorders of the neuromusculoskeletal system, it is useful to determine the repeatability of such measurements in healthy individuals and to identify where potential variability may occur.

The purpose of this study was to examine the consistency of measurements of key GRF events underlying dynamic transitions from bipedal to single-limb stance during standing single-leg flexion movements among healthy adult subjects. We hypothesized that the measurements of these events would be consistent and reproducible across subjects and, based on previous observations, would remain tightly regulated across different speeds of movement.

**Method**

**Subjects**

The subjects for this study were 18 healthy adult volunteers (10 female, 8 male) who gave informed consent. The mean age of the subjects was 31.1 years (SD=8.6), with a range of 21 to 47 years. The mean height of the subjects was 1.73 m
Kinetic data were collected at a sampling rate of 100 Hz using a PDP 11/73 computer1 with 16 A-to-D channels and 4 D-to-A channels. To evaluate instrumentation system error, the accuracy and variability of the force platforms were tested and are reported elsewhere.6 Cursor placement and graphical analysis programs were used offline to identify and quantify GRF variables for each trial as in previous studies.12,14,15

**Data Analysis**

The means, standard deviations, and ranges of the dependent variables between subjects over all trials were obtained. The GRF temporal variables (measured in milliseconds relative to the onset of unloading, as indicated by the Fz GRF component beneath the flexing limb) included onset of the propulsive phase (first change in baseline in the resultant Fy GRF, represented by line A in the Figure) and of the braking phase (the point at which the resultant Fy GRF crossed baseline and reversed sign, represented by line C in the Figure) and the time taken to unload the flexing limb (as measured by the Fz GRF recorded beneath the flexing limb, shown as line B to line D in the Figure).

The GRF magnitude variables (measured in newton-seconds) included PROP, as defined by the area under the resultant force-time curve from the onset of the propulsive phase to the point at which the curve crosses the baseline, and BRAK, as specified by the resultant force-time integral from the point at which the curve crosses the baseline (end of PROP) to the time when a steady Fy baseline is achieved (ie, the attainment of a new Fy value that fluctuates in a continuous sinusoidal manner representative of quasi-static equilibrium) during single-limb stance as identified by cursor placement (see regions PR and BR in the Figure).

Separate subject x trial two-way analyses of variance (ANOVAs) were performed using the SYSTAT statistical package6 for the five kinetic variables. Separate intraclass correlation coefficients (ICCs) were performed to determine the reliability of the data. The ICC (2,1), as described by Shrout and Fleiss,16 was utilized. Formula (2,1) was chosen because trials were considered random effects.16 Findings are thus generalizable to other trials for a particular subject. A significance level of .05 was adopted for all statistical tests.

**Results**

The group means, standard deviations, and ranges for all GRF temporal and magnitude variables across trials are summarized in Table 1. For all variables, at both fast and natural speeds of single-leg flexion, the between-subject effect was significant (P<.05) and the trial x subject interaction was not significant (P>.05). Such effects are prerequisites for the ICC to be useful in representing reliability.17

**Temporal Measures**

At fast speeds of single-leg flexion, subject x trial ANOVAs revealed moderately high ICC values for onset of the propulsive phase (ICC=.66), onset of the braking phase (ICC=.68), and time to unload the flexing limb (ICC=.71). The ICC values at the natural speed were .44, .37, and .57 for these variables, respectively. This time to unload the flexing limb ICC value was based on data from 17 of the 18 subjects because 1 subject exhibited a single statistical outlier value exceeding three and one half standard deviations from the group mean as well as that subject’s mean for the remaining values for that variable at the natural speed of movement. No other such extreme values were obtained for any of the other measurements for this subject or other subjects. When evaluating this subject’s data for the other vari-
Table 1. Group Means, Standard Deviations, and Ranges for Onset Latencies and Magnitudes of Ground Reaction Force Variables During Voluntary Single-Leg Flexion Movements in Standing (N=18)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fast Speed</th>
<th>Natural Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>SD</td>
</tr>
<tr>
<td>Latency (ms)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onset of propulsive phase</td>
<td>-217.7</td>
<td>46.4</td>
</tr>
<tr>
<td>Onset of braking phase</td>
<td>116.3</td>
<td>30.4</td>
</tr>
<tr>
<td>Time to unload flexing limb</td>
<td>199.1</td>
<td>39.7</td>
</tr>
<tr>
<td>Magnitude (N-s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PROP</td>
<td>-17.8</td>
<td>6.5</td>
</tr>
<tr>
<td>BRAK</td>
<td>15.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>

| "Negative onset latency values indicate time prior to onset of unloading beneath flexing limb. |
| "Data for natural speed are based on measurements of 17 of the 18 subjects because of outlier measurement obtained for 1 subject. |
| "Magnitude of the propulsive impulse. |
| "Magnitude of the braking impulse. |

Results are summarized in Table 2.

Magnitude Measures

Subject×trial ANOVAs for the GRF magnitudes during the propulsive and braking phases indicated high and moderately high ICC values for PROP (ICC=.93) and BRAK (ICC=.73) for the fast speed of leg flexion. At the natural speed, high ICC values were obtained for both PROP (ICC=.96) and BRAK (ICC=.88). A summary of all ICCs for the magnitude variables is provided in Table 2. Interestingly, the group mean force-time integral magnitudes for both PROP and BRAK remained essentially constant, despite significantly different times to unload the flexing limb (Tab. 1).

Discussion

The reliability of measurements of key kinetic events underlying dynamic transitions from bipedal to single-limb stance during a standing leg flexion movement in a sample of healthy adult volunteers was investigated. The results of this study suggest that certain kinetic variables, particularly those measuring the magnitude of the propulsion and braking phases of the linear momentum of the total body in the frontal plane, are very consistent and demonstrate high reliability, regardless of speed of leg flexion movement. The results also suggest that kinetic variables related to temporal measures at natural speeds of movement are less consistent and exhibit lower reliability. Moreover, to our knowledge, the findings represent the first report of the within-day repeatability of quantitative measures, reflecting key kinetic processes underlying dynamic transitions from bipedal to single-limb stance in humans.

Sources of Measurement Error

Inconsistency of a measurement may be attributable to instrumentation error, tester error, or variability in subject performance.1 Earlier examination of the measurement system6 used in this study suggests that error attributable to the instrumentation is minimal, as the root mean square of the difference between known weights applied to the force platforms and the weights determined by platform measurements was 7 N. Similarly, the standard deviation for the repeated measurements of weight was less than 3 N. Operational definitions (eg, for the onset of unloading beneath the flexing limb) of the kinetic events being studied and graphical analysis programs used in identifying and quantifying these events minimize potential error introduced by the experimenter during analysis. Furthermore, the only event in which the potential for any rater judgment would likely be greatest is the point at which the subject achieves a steady baseline value during maintenance of single-limb stance (line E in the Figure). The only variable affected by this event is BRAK (see "Reliability of..."
Magnitude Variables’ section). Therefore, the variance of the ICC values in this study was predominantly a result of variability in subject performance.

Reliability of Temporal Variables

The ICCs for the measurements of onset of the propulsive and braking phases and time to unload the flexing limb exhibited moderate reliability estimates at the fast speed of movement. In contrast, ICCs for these same variables at the natural speed exhibited the lowest reliability values obtained. The higher reliability estimates at faster speeds of leg flexion may be indicative of possible speed-related differences in the mechanical demands of the task. Because the GRF profiles reflect the mass acceleration product of all body segments, slower speeds of movement may afford a greater opportunity to alter body segment motion while flexing the leg in comparison with faster speeds. Such differences could account for the more variable temporal profile of the GRF measurements.

The speed of an intended movement has been shown to affect the latency and magnitude of electromyographic (EMG) lower-limb postural muscle responses accompanying standing arm flexion movements.18,19 Lee et al19 found highly variable postural muscle EMG onset latencies for slower versus faster intended movements of the arm as well as significant intersubject variability for the relationship of amplitude of postural muscle activity and arm acceleration. In this connection, the passive viscoelastic properties of lower-limb contractile and noncontractile tissue may play a greater role in contributing to postural and balance-related events during slower versus faster speeds. Similarly, the prolonged nature of the slower task may also subject such movements to a greater influence from peripheral sensory feedback processes, which could contribute to the increased variability observed. Moreover, self-selected slower speeds of single-leg flexion may be influenced to a great degree by individual differences such as the subject’s interpretation of movement speed. It may also be that the onset of the propulsive phase need only occur prior to unloading of the flexing limb in order to initiate the requisite lateral momentum of the CM,12 as it did in all cases, and for the onset of the braking phase to occur during unloading prior to the foot leaving the support surface.

Reliability of Magnitude Variables

The measurement of the PROP at fast and natural speeds of leg flexion exhibited the highest reliability values in this study. Clearly, these high ICC values indicate that this measurement is very consistent and reproducible among healthy adult subjects. Similarly, the measurement of the BRAK across speeds demonstrated moderate to high ICCs. The differences in the BRAK ICCs between speeds (fast, ICC = .73, natural, ICC = .88) may be attributable, in part, to the identification of quasi-static equilibrium (line E in the Figure, identified by a characteristic sinusoidal fluctuation in the Fy GRF) during the single-limb stance portion of this task. Nevertheless, these BRAK reliability estimates are also suggestive of a consistently reproducible measurement during single-leg flexion movements among healthy adult subjects.

Interestingly, PROP and BRAK magnitudes remained relatively unchanged, despite significant changes in speed of leg flexion (Tab. 1). These consistent and reproducible variables within and between subjects over a range of speeds of movement suggest that they may be tightly regulated by the movement control system within the speeds of leg flexion examined. As PROP and BRAK are respectively responsible for the initial linear motion of the CM toward the stance limb and for reducing total body motion in the frontal plane, they are likely intimately related to the control of dynamic equilibrium. Their apparently invariant nature across different speeds of leg flexion may be representative of active limitations imposed upon motion of the total body in the frontal plane related to the control of balance. Similar findings pertaining to linear momentum of the CM in the sagittal plane during a sit-to-stand task have also been reported.5

Clinical Implications

There are several advantages to using kinetic variables over gross observations or functional scales to measure human motor performance. For instance, kinetic variables can be represented on an interval or ratio scale.20 These scales allow the application of mathematical calculations (and linear statistics) while maintaining the measure’s numerical meaning.21 Furthermore, GRFs provide quantitative information regarding the dynamics as well as the quasi-static aspects of a total body movement. In contrast, clinical variables such as timed tests and functional scales generally lack the ability to elucidate on postural control mechanisms.20

In light of the consistent measurements during single-leg flexion, the clinician may draw some conclusions regarding the dynamics of this task. For example, the PROP and BRAK have been shown to be consistent within and between subjects and over a range of speeds. The PROP is a critical component in initiating and generating motion of the body CM in the frontal plane. The BRAK is likely vital for the control of balance as it relates to arresting the body momentum during dynamic transitions in stance support. Taken with recent information on patterns of hip muscle activity15 during this task, physical therapists can begin to utilize this knowledge to assess weight transfer function and balance control when evaluating movement performance.

In view of the more variable temporal GRF measurements at slower natural speeds of leg flexion, the clinician should also take into consideration the potential influence of ongoing changes in body segment motion, the passive properties of lower-limb contractile and noncontractile tissue, the possibility for a greater influence by sensory feedback processes, and a
subject's interpretation of movement speed on the outcome of the task.

Finally, there are inherent limitations in attempting to generalize conclusions directly from a task such as single-leg flexion to other functional tasks such as gait. In gait, limb withdrawal and lateral weight transfer are part of the more global activity of locomotion. Although the leg flexion task may be useful for quantifying dynamic weight transfer function in the frontal plane and for evaluating underlying movement control processes, it may be of more limited value in definitively determining the causes of more functional movement deficits.

It is striking, however, that an initial propulsion GRF profile, which is essentially identical to that found for leg flexion, is normally observed during the initiation of stepping. Furthermore, we have also found comparable PROP Py characteristics for a number of different rapid goal-directed movements that incorporate total body motion in the frontal plane (Mark W Rogers, PhD, PT; unpublished observations; 1992). Therefore, common organizational processes underlying the normal coupling of lateral motion of the body CM in conjunction with different intentional movement goals would appear to exist at the kinetic level.

Conclusions

Following a cerebrovascular accident, the single-limb stance task is often used to evaluate and train stance control in individuals with hemiparesis. We are currently investigating the dynamics of standing single-leg flexion movements within a hemiparetic population. A determination of the reliability of these GRF variables among a variety of patient populations will further advance the application of these measurements in the clinic. In addition, age-related changes in neuromusculoskeletal control processes may potentially alter the dynamics of this movement. It is appropriate to investigate the reliability of the leg flexion task in an older adult population to build upon the present research of normal changes in balance control.

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References