Lower Extremity Strength and Coordination are Independent Contributors to Maximum Vertical Jump Height

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We previously reported that lower extremity muscular strength of older adults did not predict success of a balance recovery task. We propose that lower extremity coordination may limit performance independently of lower extremity strength. The present study was conducted to determine the extent to which knee extension strength and hip–knee coordination independently contribute to maximum vertical jump height. Maximum vertical jump height and isometric and isokinetic knee extension strength and power were determined in 13 young adults. Hip–knee coordination during the vertical jump was quantified using relative phase angles. Stepwise nonlinear multiple regression determined the variable set that best modeled the relationship between the dependent variable, maximum vertical jump height, and the independent variables of strength, power, and coordination. The quadratic terms of the normalized knee extension strength at 60 deg·s⁻¹, and the average relative phase during the propulsion phase of the vertical jump, collectively accounted for more than 80% of the shared variance (p = .001). The standardized regression coefficients of the two terms, .59 and .52, respectively (p = .004 and .008), indicated the independence and significance of the contributions of knee extension strength and hip–knee coordination to maximum vertical jump height. Despite the pitfalls of extrapolating these results to older adults performing a balance recovery task, the results are interpreted as supporting the contention that while muscle strength confers a number of functional benefits, the ability to avoid falling as a result of a trip is not necessarily ensured. Increased muscle strength per se can occur in the absence of improved kinematic coordination.

Key Words: isokinetic, knee joint, phase plane, relative phase angle

Introduction

Decreased muscle strength, particularly of the lower extremities, has often been implicated as a factor underlying the increased incidence of falls by older adults. The recovery strategies of healthy older adults following an induced trip may be classified...
into two mutually exclusive categories (Pavol, Owings, Foley, & Grabiner, 2001). During-step fallers reach the criterion for a fall within 80 ms of the initial recovery-step ground contact. In contrast, after-step fallers do not reach the criterion until 400 ms after the initial recovery-step ground contact. Compared to those older adults who successfully recovered from the trip, during-step fallers were characterized by significantly faster walking velocity at the time of the trip and significantly slower response time after the instant of the trip. In contrast, after-step fallers were primarily characterized by a failure to restore control of the flexing trunk after the trip and by buckling of the recovery limb after ground contact. Contrary to expectations, particularly for after-step fallers, lower extremity muscular strength and power did not uniquely discriminate those older adults who fell after being tripped from those who did not fall (Pavol, Owings, Foley, & Grabiner, 2000).

Minimum levels of lower extremity strength and power are likely requisites for successful recovery after a trip, particularly during the support phase immediately following recovery-step ground contact. However, the failure of the comprehensive isometric, concentric, and eccentric strength measures to statistically distinguish those older adults who fell from those who did not fall raised questions regarding the clinical utility of these strength measures.

There are at least two plausible explanations for the failure of lower extremity strength to distinguish older adults who fell from those who recovered. The first explanation is that muscular strength (and power), as measured using the isokinetic dynamometer, is not specific to the muscular strength required to execute the recovery task. The second explanation is that there are additional performance variables that are critical to the success of the recovery task. For example, recovery from a trip during locomotion is a time-critical motor task. It requires a rapid transition in the recovery limb function from the swing phase to the more demanding support phase (Grabiner, Koh, Lundin, & Jahnigen, 1993). This multiarticular task requires lower extremity coordination that may not necessarily be correlated to strength. An extreme clinical example of this functional dissociation is the intact strength and significant loss of interjoint coordination in patients with large-fiber sensory neuropathy (Sainburg, Poizner, & Ghez, 1993).

The present study was conducted to test the premise that in our previous work, strength did not predict the outcome of induced trips because of the importance of lower extremity coordination to the task. To test the premise, we determined the extent to which measures of knee extension strength and hip–knee coordination independently contribute to maximum vertical jump height in young adults. We hypothesized that knee extension strength and hip–knee coordination would be independent and significant contributors to maximum vertical jump height.

**Methods**

Thirteen healthy young adults, 6 women and 7 men (mean ± SD: age 27.5 ± 9.2 yrs; 1.73 ± 0.09 m; 68.9 ± 12.1 kg) were recruited to participate in the study. The experimental methods were described prior to each participant providing informed consent.

The experiment consisted of two protocols that were completed in a single laboratory session. In one protocol the participants performed a minimum of 5 maximum vertical jump trials. A 6-camera video-based motion capture system (Motion Analysis, Santa Rosa, CA) operating at 60 Hz was used to record the motion of 12 hemispherical reflective markers placed bilaterally on the lower extremities and the trunk.
A force plate (AMTI, Newton, MA) was used to record the ground reaction forces beneath the right foot during the jumping and landing phases of the vertical jump. Sagittal plane hip and knee kinematics were derived from the recorded motion of the reflective markers. Maximum jump height, normalized to body height, was derived using force plate data and equations for uniformly accelerated motion.

A measure of hip–knee coordination during the maximum vertical jump was derived using phase plane relationships (Burgess-Limerick, Abernethy, & Neal, 1993; Hamill, van Emmerik, & Heiderscheit, 1999; van Emmerik & Wagenaar, 1996). Normalized hip and knee velocity functions were derived from the normalized hip and knee angular displacement functions (Figure 1, top panel). Normalized phase planes, with values ranging from –1 to 1, were generated for each trial by expressing normalized angular velocity as a function of normalized angular displacement (Figure 1, middle panel). Phase angles were quantified for the hip and knee at each point of the phase plane as:

$$\alpha = \arctan \left( \frac{\text{normalized angular velocity}}{\text{normalized angular displacement}} \right)$$

The relative phase angle at each point of the phase plane was calculated by subtracting each phase angle of the hip from that of the knee (Figure 1, bottom). For each participant, the relative phase angle was computed for the countermovement and propulsion phase of the vertical jump and averaged across trials. The onset of the countermovement phase was defined as movement of the hip or knee from its initial angular position. The onset of the propulsion phase was identified as the instant at which either, or both, values for the hip and knee joint angular velocity were positive, representing extension. The end of the propulsion phase was indicated when the participant became airborne as indicated by the force plate signals.

The second protocol consisted of isometric and isokinetic maximum voluntary contractions of the knee extensor muscles. Knee extension strength measurements were made on the right limb using a Kin-Com 500H isokinetic dynamometer (Chattanooga Corp., Chattanooga, TN). Participants were seated upright on the Kin-Com with the thigh-trunk angle at approximately 100°. The waist and distal right thigh were stabilized with Velcro straps. The axis of rotation of the dynamometer was aligned with the putative sagittal plane center of rotation of the right knee joint. A pad, attached to a load cell, was positioned over the lower leg proximal to the ankle joint and was secured with a Velcro strap. A threshold knee extension force of 10 lbs was required to trigger the servomechanism controlling the dynamometer motion.

Following a warm-up session in which the participants became familiar with the dynamometer, a single isometric maximum voluntary contraction (MVC) was performed with the knee positioned at 90° of flexion. Concentric isokinetic contractions were performed at velocities of 60, 150, and 240 deg·s⁻¹, the order of which was randomized. Starting with the knee positioned at 90° of flexion, the participants performed three isokinetic MVCs at each speed through a 60° range of motion. They were instructed to perform the MVCs through the entire range of motion following a verbal “Go” signal. Verbal encouragement was given throughout the trial. The force, speed, and position signals for the dynamometer were digitized at 100 Hz and stored for later processing.

The digitized force signals were transformed to knee joint moments and low-pass filtered at 10 Hz. The isometric contractions were analyzed by determining the maximum knee extension moment. The isokinetic contractions were analyzed by determining the maximum knee extension moment and maximum rate of knee moment
Figure 1 — *Top panel*: Normalized angular displacement of the hip (light line) and knee (dark line) for a maximum vertical jump initiated from a standing position from which the respective normalized angular velocities are derived. *Middle panel*: Normalized phase plane of hip (light line) and knee (dark line) for a maximum vertical jump initiated from a standing position. The phase angle of each joint, $\alpha$, is used to compute the relative phase angle. *Bottom panel*: The relative phase angle, computed by subtracting the relative phase angle of the hip from that of the knee, represents the phase lag between two joints.
generation (dM/dt) at each testing velocity. The maximum knee extension moment at each testing velocity was represented as the maximum value observed across the three trials. The dM/dt was computed as the slope of the regression equation of the moment curve calculated within a 300-ms window initiated from the onset of dynamometer motion.

Correlation analysis was used to determine the knee extension strength and the hip–knee coordination variables that best correlated with jump height. Based on expectations that relationships between knee extension strength and hip–knee coordination variables might be nonlinear, the quadratic terms of these variables were computed. The linear and quadratic strength, the dM/dt, and the linear and quadratic coordination variables having the numerically largest and statistically significant correlations were entered into a forward stepwise regression to determine which variables best predicted jump height. Inclusion in the final stepwise model reflected the statistical independence of the variables. The magnitude of the standardized regression coefficients (β) of the variables in the model were used as indices reflecting the strength of the contribution to maximum vertical jump height.

Results

The strongest relationship between isokinetic knee extension strength and maximum vertical jump height was found for the quadratic term of the maximum isokinetic strength measured at 60 deg·s\(^{-1}\) (r = 0.76, p = 0.004). However, the remaining measures of isokinetic strength and their quadratic terms were also significantly related to maximum vertical jump height (0.59 < r < 0.71; 0.01 < p < 0.04). Maximum isometric knee extension was not significantly correlated to maximum vertical jump height (r = 0.56, p = 0.06). None of the measures of dM/dt were significantly correlated to maximum vertical jump height (0.26 < r < 0.46; 0.13 < p < 0.42).

The quadratic term of the average relative phase angle during the propulsion phase was significantly correlated to the maximum vertical jump height (r = 0.71, p = 0.01). The linear term of the average relative phase angle during the propulsion phase was also significantly correlated to the maximum vertical jump height, although the magnitude of the correlation was smaller (r = –0.64, p = 0.03). The linear and quadratic terms of the average relative phase angle during the countermovement phase were not significantly correlated to the maximum vertical jump height (r = –0.49 and 0.03, p = 0.10 and 0.92, respectively). The relationship between the average relative phase angles during the countermovement and during the propulsion phases were not significant (–0.04 < r < 0.47; 0.12 < p < 0.89).

The quadratic terms of the knee extension strength at 60 deg·s\(^{-1}\) and hip–knee coordination during the propulsion phase were not significantly correlated to each other (r = 0.32, p = 0.31). The independence and significance of these measures of knee extension strength and hip–knee coordination to maximum vertical jump height was reflected by the inclusion of the two selected terms in the calculation of the regression equation.

Vertical jump height (% body height) = 0.314 + (0.036 · maximum isokinetic knee strength\(^2\)) + (0.0015 · hip–knee coordination during propulsion phase\(^2\)).

In the stepwise regression, the quadratic terms of the normalized knee extension strength at 60 deg·s\(^{-1}\) and the average relative phase during the propulsion phase of
the vertical jump collectively accounted for more than 80\% of the shared variance (adjusted $R^2 = 0.77$, $p = .001$). The standard error of the estimate was 0.027. The standardized regression coefficients, $\beta$ of the two terms were .59 and .52 ($p = .004$ and .008), respectively.

**Discussion**

The purpose of this study was to determine the extent to which measures of knee extension strength and hip–knee coordination independently contribute to maximum vertical jump height in young adults. The results indicate that the contributions of knee extension strength and hip–knee coordination to maximum vertical jump height are indeed independent and significant. Furthermore, the $\beta$-coefficients demonstrate that knee extension strength and hip–knee coordination were reasonably similar with respect to the extent of their mathematical contributions to maximum vertical jump height.

The motive for conducting this study was our previous finding that measures of isometric and isokinetic lower extremity strength did not discriminate older adults who fell following an induced trip from those who successfully recovered. We considered the possibility that measures of strength obtained from an isokinetic dynamometer do not reflect the type of strength required to execute the recovery task, particularly during the support phase following recovery-foot ground contact.

An explanation for the nonspecificity could be the open chain characteristics of the dynamometer task versus the closed chain characteristics of the support phase of the recovery task. This seems plausible in light of the equivocal findings reported by others. For example, isokinetic strength has been reported to be weakly to strongly related to single-legged jumping for distance (Greenberger & Paterno, 1995; Pincivero, Lephart, & Karunakara, 1997). In contrast to our findings, the strength of these relationships increased with isokinetic velocity. The differences in the motor tasks may be a factor. In another study, isotonic knee extension strength was reported to be very weakly correlated to maximum vertical jump performance ($r = 0.01$, Blackburn & Morrisey, 1998). Nevertheless, our results showed that maximum isokinetic knee extension strength at 60 deg·s$^{-1}$ was significantly correlated to maximum vertical jump height.

If our observed relationship between measures of open chain muscular strength and performance of a closed chain motor task can be extrapolated to older adults, the second of our previous explanations for our prior results becomes stronger. Specifically, additional performance variables that can vary independently of strength are concurrent contributors to the successful execution of recovery. We considered that the sagittal plane hip–knee coordination as measured using phase plane analysis is such a performance variable. The qualitative dissociation between upper extremity coordination, as measured with phase plane analysis and upper extremity muscle strength, has been shown in patients with large-fiber sensory neuropathy (Sainburg et al., 1993). Our results confirm that lower extremity strength and coordination during a rapid multiarticular task are independent ($r = 0.32$, $p = 0.31$).

Not surprisingly, the results indicate that independent of muscle strength, maximum vertical jump height can be substantially diminished by altered hip–knee coordination. We recognize the pitfalls of extrapolating these results to a very different population of participants performing a very different motor task. Nevertheless, we interpret the results as supporting the contention that while muscle strength confers a
number of functional benefits, it does not necessarily ensure the ability to avoid falling due to a trip. Increased muscle strength, per se, can occur in the absence of improved kinematic coordination. However, as it relates to older adults in general and the issues related to preventing falls in older adults, this is a hypothesis that merits further systematic population-specific and task-specific investigation.

References


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