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The lower extremity dexterity test as a measure of lower extremity dynamical capability

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ABSTRACT

The capability of the lower extremity to dynamically interact with the ground is important for skilled locomotor performance. However, there is currently no test method designed to specifically quantify this sensorimotor ability, which we refer to as lower extremity dexterity. We describe a new method to quantify lower extremity dexterity, examine its reliability ($n=10$), and evaluate the extent to which it is associated with lower extremity strength and anthropometry in healthy young adults ($n=38$). The lower extremity dexterity test (LED-test)—an adaptation of the Strength–Dexterity test for the fingers–consists of using the isolated lower extremity to compress a slender spring prone to buckling at low forces. The goal of the LED-test is to sustain the highest compression force possible. Applying higher forces makes the spring increasingly unstable, thus achieving higher compression forces represents better ability to dynamically control instability at low force levels. As such, the LED-test provides a novel way to quantify the capability of the lower extremity to regulate dynamic and unstable foot-ground interactions at submaximal forces. LED-test performance ranged between 88.6 and 119.6 N, test-retest reliability was excellent ($\mathrm{ICC}_{(2,3)}=0.94$), and the minimal detectable difference was 5.5 N. Performance was not correlated with strength or height ($r^2 \leq 0.053$, $p > 0.05$), and only weakly with body mass ($r^2=0.116$, $p=0.04$). We propose that the unique lower extremity capability quantified by the LED-test could be informative of skilled locomotor performance and injury risk.

1. Introduction

Dynamic interactions between the lower limb and the environment are required to control and redirect body center of mass movement during walking, running, rapid turning, and landing (Hass et al., 2008; Kaya et al., 2006; Liu et al., 2008; Mathiyakom et al., 2006). Therefore, it is conceivable that the capability to regulate the dynamic interactions between the foot and ground could underlie locomotor skill and injuries that occur during sudden deceleration and change of direction maneuvers. While biomechanical measurements (e.g. center of pressure, kinematics, kinetics) can characterize joint and whole body dynamics, there is currently no test method designed to objectively quantify the sensorimotor ability we refer to as lower extremity dexterity. We operationally define lower extremity dexterity as the capability of the isolated lower limb to dynamically regulate endpoint force magnitude and direction when interacting with the environment (Valero-Cuevas et al., 2003).

We propose a new method to quantify lower extremity dexterity that is based on the Strength–Dexterity test (S–D test) designed to quantify dynamic finger pinch capability (Valero-Cuevas et al., 2003; Venkadesan et al., 2007). The S–D test involves compressing a slender spring with the fingertips as far as possible without buckling, which requires precise control of fingertip motions and force vector direction at submaximal forces. The S–D test has been shown to discriminate between older adults with and without thumb osteoarthritis (Valero-Cuevas et al., 2003), and recently has been validated as a metric of hand dexterity in children (Vollmer et al., 2010). Moreover, evidence suggests that the S–D test quantifies a unique construct (i.e. dexterity) that is reflective of sensorimotor processing for skilled finger function because it is independent of strength (Valero-Cuevas et al., 2003; Venkadesan et al., 2007; Vollmer et al., 2010), is affected by development and aging (Vollmer et al., 2010), and engages distinct cortico-striatal–cerebellar networks in a context-sensitive way (Mosier et al., 2011). Given that dynamic interactions between the foot and ground are similar to dexterous manipulation in principle, we

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adapted the S–D test approach to quantify lower extremity dexterity.

The current study had three objectives. First, we describe the test method designed to quantify lower extremity dexterity (the LED-test). Second, we assessed reliability of LED-test performance. Lastly, we examined the extent to which LED-test performance is associated with strength and anthropometry.

2. Methods

2.1. Subjects

Thirty-nine subjects (19 females, 20 males) between the ages of 15 and 25 participated in this study (age: 17.7 ± 3.1 years, height: 1.74 ± 0.09 m, mass: 66.8 ± 10.2 kg). Participants were excluded if they had a previous knee surgery or recent injury that prevented participation without pain. One male subject was excluded because he did not complete an adequate number of successful trials of the LED-test (see methods and results). All subjects provided written informed consent as approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Prior to testing, height and body mass were recorded and participants were fitted with the same style of athletic shoe (New Balance Inc., Boston, MA). This was done to mitigate the potential influence of footwear. Participants completed the LED-test, as well as hip and knee strength testing during a single testing session. Only the dominant lower extremity was tested (i.e. preferred foot to kick a ball). To assess test-retest reliability and precision, 10 of the subjects repeated the LED-test on a separate occasion separated by a minimum of 3 and maximum of 9 days (average: 5.1 ± 2.2 days).

2.2. LED-test design and analysis

The LED-test is a dynamic contact control task that is based on the ability of participants to compress a slender spring prone to buckling (Valero-Cuevas et al., 2003; Venkadesan et al., 2007). The LED-test device consisted of a 25.4 cm helical compression spring prone to buckling mounted within plastic endcaps and fastened to a stable base (i.e. fixed end) with a 20 × 30 cm platform affixed to the free end (Fig. 1). The spring characteristics were as follows: mean diameter: 3.08 cm, wire diameter: 0.04 cm, spring rate: 36.8 N/cm, total coils: 28.7, hard drawn wire (♯850, Century Spring Corp., Los Angeles, CA). The spring parameters (i.e. stiffness and slenderness) were chosen such that spring instability occurred at low forces in an effort to minimize the influence of lower extremity strength on performance and mitigate fatigue. The test device was positioned on a force plate and the vertical ground reaction force component was recorded at 1500 Hz (AMTI, Waterton, MA). The raw vertical ground reaction force was low-pass filtered with a 4th order Butterworth filter at 15 Hz and displayed as force feedback using LabVIEW (National Instruments Corp., Austin, TX).

The LED-test was performed as shown in Fig. 2. Participants were positioned in an upright partially seated posture on a bicycle saddle and were supported at the trunk by leaning forward approximately 20° against a strap at the level of the xiphoid process. The non-tested foot rested on a step which was adjusted so that the hip and knee were extended (0°) and the pelvis was level. Individuals were instructed to support their weight equally through the bicycle saddle and the non-test limb so as to unload the leg being tested. The forearms rested on a crossbar adjusted to the level of the xiphoid process. Subject positioning was intended to be stable and minimize the extraneous use of the contralateral limb and upper extremities during testing. The test limb was positioned with the foot on the device platform in a standardized posture (i.e. 75–80° of hip and knee flexion). Because the test device height was constant, the standardized joint angles were achieved across subjects by adjusting the height of the bicycle saddle and the step under the non-tested limb. Foot position on the platform was standardized such that the midline of the platform in the mediolateral and anteroposterior directions was aligned with the second metatarsal and the navicular bones, respectively. A computer monitor provided visual force feedback of the vertical force (Fig. 2).

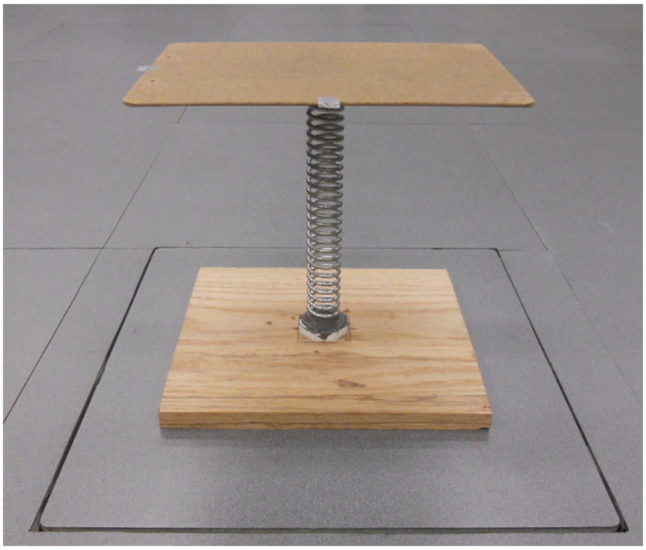

Fig. 1. Test device for the lower extremity dexterity test.

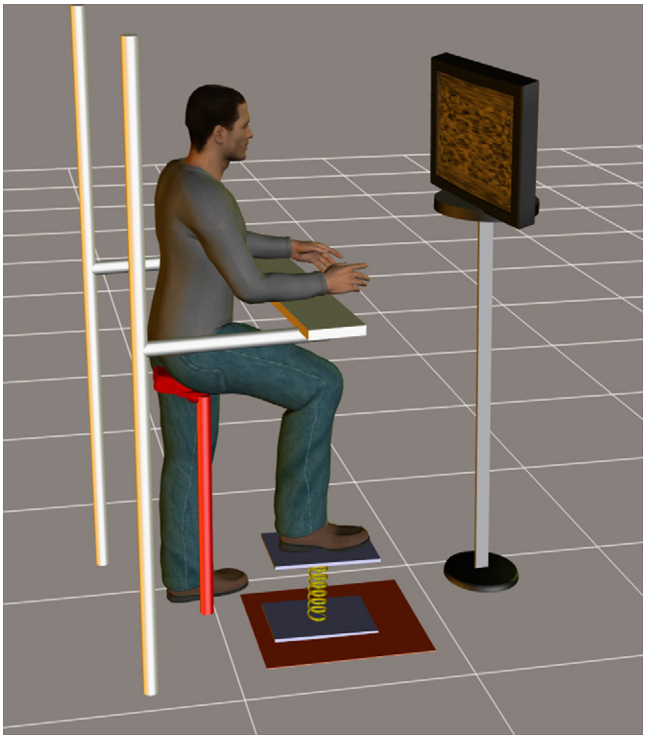

Fig. 2. Schematic of experimental set-up for the lower extremity dexterity test. The test limb posture was standardized (i.e. hip and knee flexion angles between 75–80°) with the foot positioned on the test device. The posture was achieved across participants by adjusting the seat height and placing the non-tested foot on a step so that the non-tested hip and knee were extended and the pelvis was level (see methods for complete description).

Prior to testing, participants were familiarized with the force feedback system by performing 5 practice trials. Participants were instructed to slowly compress the spring with their foot with the goal to raise the force feedback line as high as possible (i.e. proxy to maximize the instability of the device) without moving their foot relative to the platform. Participants were informed that it is natural for the spring to bend and become unsteady. Despite the inherent instability of the spring, the goal was to achieve and sustain the highest vertical force possible during each 16 s trial.

The dependent variable for the LED-test was the highest average vertical force over a 10 s period during the sustained hold phase of each trial. The maximal value was identified for each trial using a point-by-point 10 s moving average calculated from the raw vertical ground reaction force (Fig. 3) (Venkadesan et al., 2007). Maximal values were determined using a custom program written in MATLAB (The Mathworks, Natick, MA), and were considered for analysis if the coefficient of variation was $\leq 10\%$ for each moving window time step. The coefficient of variation criterion was chosen as an indicator of performance stability (Venkadesan et al., 2007). While it may appear that the foot would be quasi-static during the hold phase, the leg-platform system is in fact a nonlinear system undergoing constant dynamic adjustments of motions and forces.

After the 5 familiarization trials, subjects completed between 21 and 25 trials. Testing was stopped after trial 21 if performance on this trial was not among the best 3 of the previous 20 trials. Additional trials were completed up to 25 if performance on the 21st trial was one of the top 3 achieved. The number of trials was selected based on pilot testing that demonstrated best performance typically was achieved within 20–25 attempts. To assure that test performance had

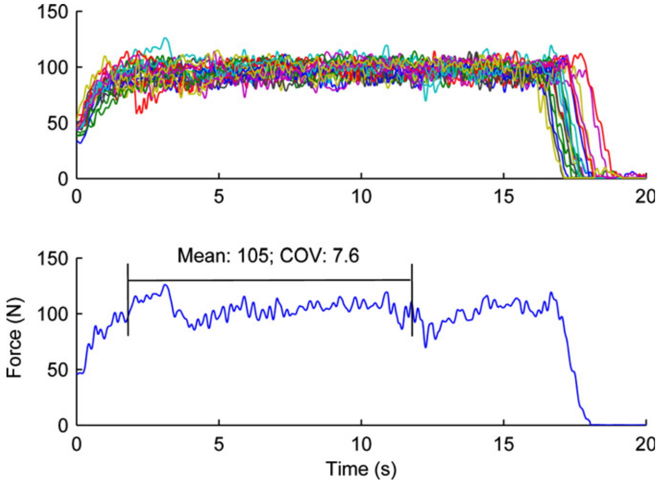

Fig. 3. Example of data analysis for the LED-test. The top graph illustrates a time series of raw force data from a representative subject with each color representing a different trial. The bottom graph illustrates a time series from a single trial with the vertical black bars denoting the moving window period in which the maximal force value (Newtons) was identified and the coefficient of variation (COV) of the force values within the window. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

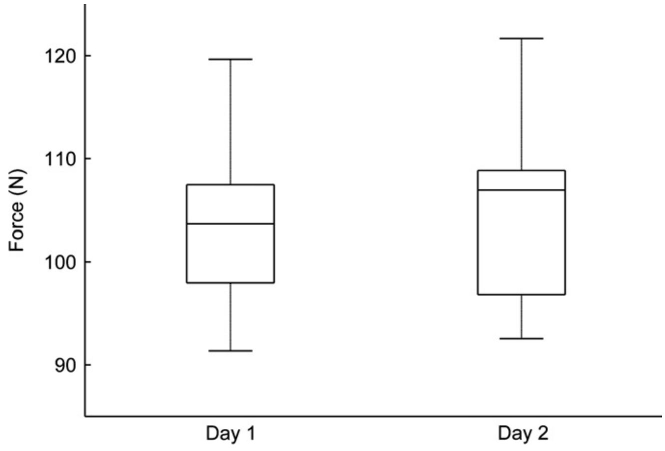

Fig. 4. Test-retest reliability results ($n=10$). No difference was observed in LED-test performance across days ($P=0.13$). The central horizontal line within the box represents the median value, the box edges represent 25th and 75th percentile, and the whiskers represent the outermost data points.

stabilized, we required that subjects complete at least 15 trials that met the coefficient of variation criterion. Failure to meet this criterion resulted in a subject being excluded from the analysis. The average of the best 3 trials was used for analysis.

Throughout testing, subjects were instructed to avoid using the contralateral limb or arms to help direct the movement of the test limb. To minimize physical and mental fatigue, 30 s of rest was provided between trials and 2 min of rest was provided after every 5th trial. Verbal encouragement was provided to facilitate maximal performance.

2.3. Lower extremity strength

Peak isometric torque was obtained for the knee extensors, knee flexors, and hip extensors using a Humac Norm Dynamometer (CSMi, Stoughton, MA). For knee extensor and flexor strength, subjects were seated with the hip at 90° and the knee flexed to 60°. The thigh was secured to the dynamometer seat with a strap. The resistance pad was placed just proximal to the ankle. Hip extension strength was evaluated in the prone position with the pelvis supported at the edge of the dynamometer testing table and the hip in 60° of flexion. Participants were asked to extend their hip into a resistance pad positioned against the posterior thigh with the knee flexed to 90°. To facilitate a maximal effort, real-time torque was displayed as feedback during each trial and verbal encouragement was provided. One practice trial was provided for each testing position. Three maximal effort trials consisting of 5 s holds were then recorded. A rest period of ≥30 s was provided between trials. The maximal torque value obtained from each muscle group was divided by body mass and used for statistical analyses.

2.4. Statistical analysis

Test-retest reliability of LED-test performance was assessed using the intraclass correlation coefficient, $\text{ICC}_{(2,3)}$. Test precision was assessed using standard error of the measurement [$\text{SEM}=\text{SD}\sqrt{(1-\text{ICC})}$] and the minimal detectable difference [$1.96\times\text{SEM}\times\sqrt{2}$] (Denegar and Ball, 1993; Portney and Watkins, 2009). In addition to test-retest reliability, a paired-*t* test was used to determine whether performance differed between days. Pearson correlation coefficients reported as the coefficient of determination (r^2) were used to examine the relationships between LED-test performance and strength, body mass, and body height. Statistical analyses were performed with SPSS software (IBM, Armonk, NY) using a significance level of $p\leq 0.05$.

3. Results

3.1. Test-retest reliability

The average forces achieved by participants during the LED-test were similar across days (103.4 ± 8.4 vs. 105.3 ± 8.8 N, $p=0.13$, Fig. 4). Performance on the LED-test had a test-retest reliability of $\text{ICC}_{(2,3)}=0.94$. The standard error of the measurement was 2.0 N. The minimal detectable difference was 5.5 N.

3.2. Association with strength and anthropometry

One male participant was excluded from this analysis because he did not complete the minimum of 15 LED-test trials that met the coefficient of variation criterion of 10%. Across all participants, LED-test performance ranged between 88.6 and 119.6 N. LED-test performance was not significantly associated to hip and knee muscle strength (Table 1). Although LED-test performance was not correlated with height, a small but statistically significant correlation was found between LED-test performance and body mass ($r^2=0.12$, $p=0.04$).

4. Discussion

The goal of this study was to describe a novel test method to quantify the dynamical capability of the lower extremity to regulate foot-ground interactions. Given that the instability of a slender spring increases with increasing compression forces, we propose that the highest sustained vertical force achieved during the LED-test is representative of the maximal sensorimotor ability to dynamically regulate contact with the unstable spring-platform system at submaximal force levels. In support of this premise, performance was independent of lower extremity strength suggesting that the ability to coordinate muscles to dynamically regulate force direction is more important for LED-test performance. This finding is consistent with previous investigations that have used this paradigm to assess sensorimotor capability for dynamic dexterous manipulation (Valero-Cuevas et al., 2003; Venkadesan et al., 2007; Vollmer et al., 2010).

It should be noted that we did not evaluate the influence of all lower limb muscles that could function to stabilize the limb (e.g. hip abductors). Differential strength of muscles not evaluated in this study could have influenced LED-test performance and should be examined in future work. It is important to emphasize, however, that the overall finding that test performance is independent of strength supports our design goal to measure sensorimotor ability without the confound of muscle strength.

With respect to the association between anthropometric measures and LED-test performance, body height was not correlated with LED-test performance. Although a small but significant statistical correlation was found between LED-test performance and mass, this association only explained 11.6% of the variance in

Table 1
Correlation between LED-test performance and strength and anthropometry. ($n=38$).

	Hip extensor strength	Knee extensor strength	Knee flexor strength	Body mass	Height
LED-test performance	$r^2=0.036$ $p=0.26$	$r^2=0.002$ $p=0.75$	$r^2=0.019$ $p=0.41$	$r^2=0.116$ $p=0.04$	$r^2=0.053$ $p=0.17$

LED-test performance. As such, body mass was not a meaningful determinant of LED-test performance in the sample tested here. It is possible, however, that the relation between body mass and LED-test performance may differ in populations with larger body mass.

Dynamic interactions between the lower limb and environment are required to change speed and direction during locomotion and skilled whole-body tasks (Hass et al., 2008; Kaya et al., 2006; Liu et al., 2008; Mathiyakom et al., 2006). Therefore, we speculate that dynamic lower extremity control as assessed by the LED-test could be informative of the capability to perform activities that require dynamic foot-ground interactions. Although the LED-test does not mimic dynamic functional tasks in terms of force magnitudes or whole-body mechanical demands in a traditional sense, the regulation of such task features are in principle very much related to the goal of the LED-test. In fact, the original S–D test for the hand was specifically designed to disambiguate the effects of muscle strength from those of dynamic sensorimotor processing capability. Similarly, the LED-test was designed to quantify the dynamic sensorimotor coordination required to regulate foot-ground interactions at low forces. This was done to target sensorimotor processing, which plays an important role in the regulation of dynamic foot-ground interactions when quickly controlling and redirecting the center of mass during whole-body dynamical maneuvers.

The LED-test and its conceptual framework open new opportunities to quantify dynamic lower extremity control that may underlie functional mobility. The ability to maximally challenge the sensorimotor system using this approach has been informative of dexterous manipulation for hand function (Mosier et al., 2011; Valero-Cuevas et al., 2003; Venkadesan et al., 2007; Vollmer et al., 2010), and we anticipate that further development of the LED-test will advance the understanding of able and impaired lower extremity dexterity. A unique feature of the LED-test is its ability to quantify the dynamical capability of the lower extremity at the limits of sensorimotor performance in a safe manner. The supported posture used for the LED-test mitigates safety concerns of high demand functional tasks and potential confounds such as balance and fear avoidance inherent to functional task evaluations, thereby enabling individuals to exhibit their true lower extremity capability. In addition, the large force magnitudes and mechanical demands associated with the performance of dynamic whole body tasks may in fact confound attempts to quantify sensorimotor ability of the lower extremity due to within and between subject variability. As such, we anticipate that the LED-test could provide a safer and potentially more sensitive way to identify impairments in the capability of the lower extremity to regulate foot-ground interactions that could have implications for motor skill and injury risk (e.g. older adults at risk for falls).

There are advantages and potential limitations concerning the experimental testing position chosen for the LED-test. The primary advantage as previously suggested is that the LED-test allows insight concerning the dexterity of the relatively isolated lower limb. We limited the influence of the non-tested limbs and trunk on LED-test performance by standardizing the test posture and asking subjects to not use the upper limbs or non-tested lower limb to help direct the test limb. It was necessary to provide these constraints so that limb dexterity (i.e. LED-test performance) as defined and assessed in this study could be evaluated as an independent factor relevant for motor skill. It is important to note that we did not monitor interaction forces between the non-tested limbs and support surfaces during testing.

The LED-test was performed with the hip and knee joints flexed to 75–80° to start each trial. Although performing the LED-test in a more extended posture would be more comparable to functional tasks such as walking we found this position to be impractical as participants would tend to lock their knee in extension during testing. The goal of the LED-test was not to imitate "real world" conditions for a particular task, but rather to quantify sensorimotor capability in a general sense. Thus the posture and task that we used is explicitly designed to allow the subject every advantage to exercise their maximal sensorimotor stabilizing capabilities, without confounds such as locking joints, balance control, etc.

The dynamics of the spring-platform system comprise a complex and highly nonlinear interplay between spring compression and the posture of the board (Venkadesan et al., 2007). The board position was not explicitly constrained during the test, but it was apparent to all participants that there were implicit constraints of where the board could be positioned such that they could produce force without foot slipping. As is the case with nonlinear dynamical systems undergoing a bifurcation (e.g., weather patterns, aircraft wing flutter), measurable parameters like tilt angles, velocities, and accelerations cannot be used to quantify these highly nonlinear processes (Guckenheimer and Holmes, 1983). Thus, it is currently not possible to determine what tilt in the upper contact board was tolerable before the spring buckled or how those tolerable angles may have changed as the spring was compressed. It should be noted that the goal of the task was not to keep the spring centered or straight. Rather, the goal was to compress the spring as far as possible while dynamically adjusting lower limb motions and forces in response to the instability. In fact, one of the virtues of this novel method is that it embraces and exploits the nonlinearity of the brain-leg-spring system to provide a simple metric of lower limb sensorimotor function, similar to what we have found for hand dexterity (Mosier et al., 2011; Valero-Cuevas et al., 2003; Venkadesan et al., 2007; Vollmer et al., 2010).

Conflict of interest statement

FVC holds Unites States Patent 6,537,075 on a device for developing and measuring grasping force and grasping dexterity.

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References

Denegar, C.R., Ball, D.W., 1993. Assessing reliability and precision of measurement: an introduction to intraclass correlation and standard error of measurement. Journal of Sport Rehabilitation 2 (1), 35–42.

Guckenheimer, J., Holmes, P., 1983. Nonlinear Oscillations, Dynamical Systems, and Bifurcations of Vector Fields. Springer-Verlag, New York, N.Y.

Hass, C.J., Waddell, D.E., Wolf, S.L., Juncos, J.L., Gregor, R.J., 2008. Gait initiation in older adults with postural instability. Clinical Biomechanics 23 (6), 743–753.

Kaya, M., Leonard, T.R., Herzog, W., 2006. Control of ground reaction forces by hindlimb muscles during cat locomotion. Journal of Biomechanics 39 (15), 2752–2766.

Liu, M.Q., Anderson, F.C., Schwartz, M.H., Delp, S.L., 2008. Muscle contributions to support and progression over a range of walking speeds. Journal of Biomechanics 41 (15), 3243–3252.

Mathiyakom, W., McNitt-Gray, J.L., Wilcox, R., 2006. Lower extremity control and dynamics during backward angular impulse generation in forward translating tasks. Journal of Biomechanics 39 (6), 990–1000.

Mosier, K., Lau, C., Wang, Y., Venkadesan, M., Valero-Cuevas, F.J., 2011. Controlling instabilities in manipulation requires specific cortical-striatal-cerebellar networks. Journal of Neurophysiology 105 (3), 1295–1305.

Portney, L.G., Watkins, M.P., 2009. Foundations of Clinical Research: Applications to Practice. Pearson/Prentice Hall, Upper Saddle River, N.J.

Valero-Cuevas, F.J., Smaby, N., Venkadesan, M., Peterson, M., Wright, T., 2003. The strength–dexterity test as a measure of dynamic pinch performance. Journal of Biomechanics 36 (2), 265–270.

Venkadesan, M., Guckenheimer, J., Valero-Cuevas, F.J., 2007. Manipulating the edge of instability. Journal of Biomechanics 40 (8), 1653–1661.

Vollmer, B., Holmstrom, L., Forsman, L., Krumlinde-Sundholm, L., Valero-Cuevas, F.J., Forssberg, H., Ullen, F., 2010. Evidence of validity in a new method for measurement of dexterity in children and adolescents. Developomental Medicine and Child Neurology 52 (10), 948–954.