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Short communication

The strength–dexterity test as a measure of dynamic pinch performance

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Abstract

We have developed a method to quantify the dynamic interaction between fingertip force magnitude (strength) and directional control (dexterity) during pinch with a novel strength–dexterity (S–D) test based on the principle of buckling of compression springs. The test consists of asking participants to use key and opposition pinch to attempt to fully compress springs, in random order, with a wide range of combinations of strength and dexterity requirements. The minimum force required to fully compress the spring and the propensity of the spring to buckle define the strength and dexterity requirements, respectively. The S–D score for each pinch style was the sum of the strength values of all springs successfully compressed fully. We tested 3 participant groups: 18 unimpaired young adults ($\leqslant$40 yr), 10 unimpaired older adults ($>$40 yr), and 14 adults diagnosed with carpo-metacarpal osteoarthritis (CMC OA) ($\geqslant$36 yr). We investigated the repeatability of the S–D test with 74 springs by testing 14 young adults twice on different days. The per-spring repeatability across subjects was $\geqslant$94%. A minimum performance score for young adults was found as they all could compress a subset of 39 springs. Using this subset of springs, we compared the ability of the S–D score vs. maximal pinch force values to distinguish unimpaired hands from those with CMC OA of the thumb. The score for this 39-spring S–D test distinguished between CMC OA and asymptomatic older adults, whereas pinch meter readings did not ($p<0.05$). We conclude that the S–D test is repeatable and applicable to clinical research. We propose including the S–D test in studies aiming to quantify impairment and compare treatment outcomes in orthopaedic and neurological afflictions that degrade dynamic manipulation.

Keywords: Hand; Pinch; Motor control; Functional evaluation; Clinical

1. Introduction

The effectiveness of dynamic pinch—particularly for the lightweight objects of daily life—depends on the ability of the fingers (and thumb) to produce fingertip forces with sufficient magnitude and directional control (Valero-Cuevas et al., 1998; Valero-Cuevas, 2000b). Fingertip force vectors must be of sufficient magnitude to prevent slipping in the presence of gravity and other external loads; and must be well directed to oppose the actions of the other fingers and external perturbations. This allows the fingers to withstand perturbations and dynamically impart accelerations to objects according to the demands of manipulation tasks (Cutkosky, 1983; Murray et al., 1994).

Available measures of manipulation focus on maximal static forces or whole-arm tasks and, thus, cannot directly quantify the dynamic quality of fingertip forces during manipulation. Measuring maximal static pinch force is well established (Mathiowetz et al., 1985; Totten and Flinn-Wagner, 1992; Fess, 1995). However, because most daily tasks require sub-maximal and dynamic pinch forces, maximal static pinch force alone cannot quantify the dynamic sensorimotor integration necessary to produce the magnitude and directional control of finger forces critical to the effectiveness of dynamic pinch. Available tests of hand-eye or reach-to-grasp coordination (e.g., Purdue Pegboard Test,

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Jebsen-Taylor Hand Function Test (Totten and Flinn-Wagner, 1992; Fess, 1995)) are not specific enough to finger function because they involve the entire upper extremity and are susceptible to adaptive strategies. The clinical evaluation of the fingers (e.g., range of motion, two-point discrimination (Jones, 1989)) or questionnaires that rely on subjective verbal reports of hand function (e.g., DASH (disabilities of arm, shoulder, and hand) (Amadio, 1997; Navsarikar et al., 1999)) do not directly quantify the contribution of the fingers to the effectiveness of dynamic pinch.

We have developed a method to quantify the dynamic interaction between fingertip force magnitude (strength) and directional control (dexterity) during pinch, which we call the S–D test. We now present the concept, design and repeatability of the S–D test, plus a sample clinical application to patients with carpo-metacarpal osteoarthritis (CMC OA).

2. Methods

The method is based on the ability of participants to use pinch to fully compress a compression spring prone to buckling. A sufficiently slender compression spring will buckle when shortened below a critical length (Haringx, 1948; Wahl, 1963; Samónov, 1980; Shigley and Mischke, 1989). The S–D test consists of asking participants to use key and opposition pinch to attempt to fully compress a set of springs with plastic end caps (Fig. 1) embodying a wide range of combinations of strength and dexterity requirements (Valero-Cuevas, 2000a). After the participant attempts to compress each spring three times to its solid length (when the coils are all in contact with one another) using key or opposition pinch, a binary score is used to record if they succeeded at least once. The pinch force necessary to compress the spring to solid length defines the *strength requirement*. The ability to compress the spring without buckling defines the *dexterity requirement*. To prevent buckling, the motion of the fingers and the direction of fingertip forces need to be dynamically regulated to create the necessary end condition requirements at the end caps. The greater the propensity of a spring to buckle, the more precisely the end caps need to be held parallel and aligned, and the more accurately the fingertip forces need to be directed to correct any perturbation. The dexterity index quantifies the dexterity requirement

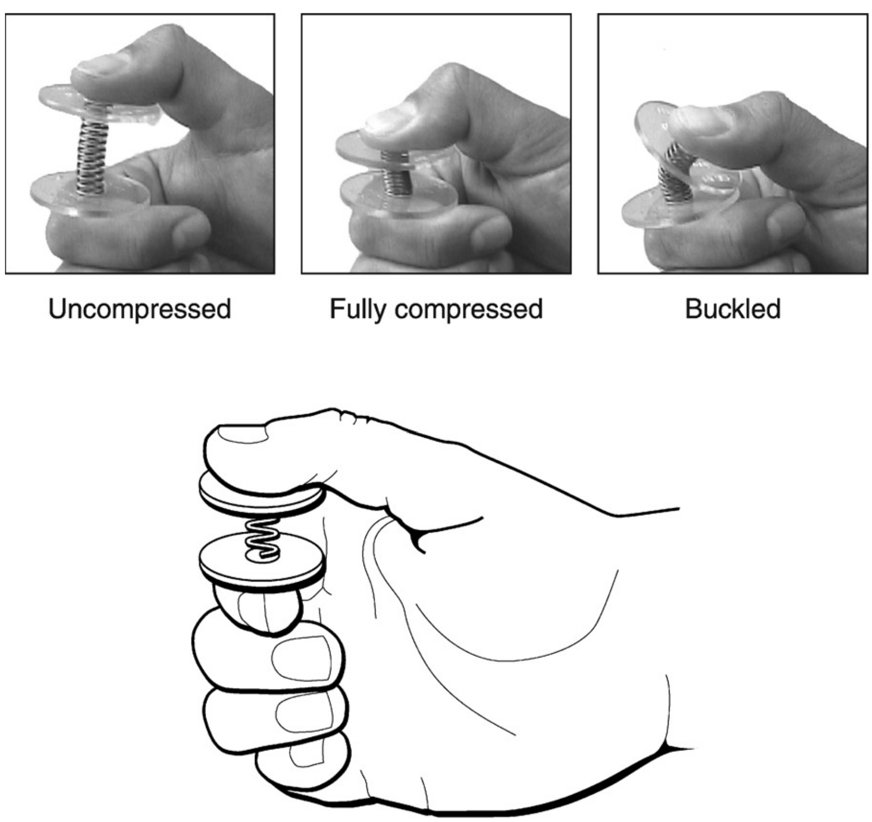

Fig. 1. Compressing a spring with end-caps in key pinch. Fully compressing a helical spring with forces emanating from the fingers requires (i) that the magnitude of opposing forces overcome the stiffness of the spring, and (ii) that the opposing forces be sufficiently well aligned with the longitudinal axis of the spring. Top left: uncompressed spring. Top center: successful compression. Top right: buckling of spring due to inappropriate fingertip forces.

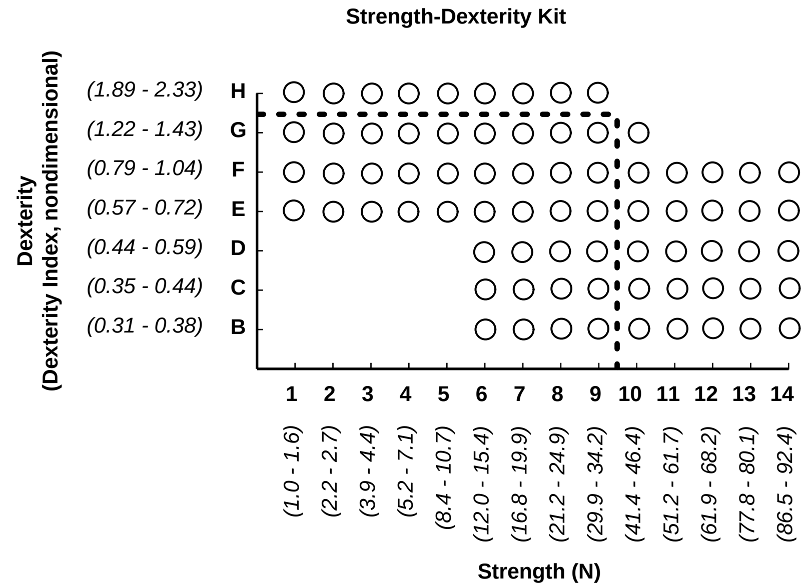

Fig. 2. The springs in the S–D kit. We approximated the S–D plane by 74 springs (open circles) with free lengths ranging from 20 to 27 mm, each representing a different combination of stiffness and dexterity index. The strength requirements were chosen to represent 14 levels (designated by numbers from 1 to 14 for values from 1 to 92.4 N, see axis labels). We chose seven levels of dexterity indices ranging from 0.31 (row B: the spring will never buckle even with both ends free to rotate and shift) to 2.33 (row H: the spring can buckle when both ends are held parallel to each other), see axis labels. The higher the dexterity index, the greater its sensitivity to manufacturing tolerances becomes, and the greater the range in values for each row of the S–D Kit when using off-the-shelf commercial springs. Row A was left intentionally blank in case future uses warrant the inclusion of a lower dexterity level for severely impaired populations. In this study, a clear pattern emerged where every unimpaired young adult was able to compress all springs in a region of the grid bounded by G on the top and 9 on the right (dashed line, referred to as the core region), indicating the presence of a minimum rectangle of performance for unimpaired young adults. The springs in the core region make up the 39-spring S–D kit.

(i.e., propensity to buckle):

$$\text{Dexterity} \quad \text{index} = \frac{1}{D \cdot C_1}\sqrt{\frac{2 \cdot y_{\max} \cdot C_1 \cdot L_0 - y_{\max}^2}{C_2}}, \quad (1)$$

where D is the mean diameter of the spring, C_1 and C_2 are constants that depend on the spring material, and L_0 is the free length of the spring (Samónov, 1980; Shigley and Mischke, 1989). For a given spring, $y_{\max}$ is the maximal distance the spring can be shortened before reaching solid length. For example, a dexterity index of one indicates that, to be able to compress the spring to the spring a distance $y_{\max}$ without buckling, the subject must either perfectly control the orientation of the end plates *or* their positions. A dexterity index of two requires perfect control of *both* position and orientation for the spring not to buckle before $y_{\max}$. Note that the strength and dexterity requirements are independent in the sense that one can design a group of springs (by selecting the number of coils, spring diameter, wire diameter, material, etc.) with the same free length and strength requirements, but where each spring has a different dexterity index for the same amount of compression (i.e., $y_{\max}$) . Thus, every possible combination of strength and dexterity is a point on the S–D plane defined by two orthogonal axes representing strength and dexterity (Fig. 2). We selected 72 off-the-shelf commercial springs that have the desired dexterity index close to solid length so that the easily detectable event of reaching solid length indicates the subject achieved the desired dexterity index at the specified maximal spring force. Thus, noting if the subject was able to compress a spring to solid length indicated if the subject met a particular combination of strength and dexterity requirements, without needing to measure end cap position and orientation during spring compression.

The subject pool consisted of 42 participants: 18 unimpaired adults under the age of 40 yr (mean age 22 ± 5 yr, range 18–39, 9 males, 9 females), 10 unimpaired adults over the age of 40 yr. (mean age 54 ± 13 yr, range 40–78, 2 males, 8 females), and 14 adults with CMC OA without neurological co-morbidities such as carpal tunnel syndrome (mean age 65 ± 12 yr, range 50–79, 4 males, 10 females). All participants read, understood and signed the consent form approved by the University Committee on Human Subjects at Cornell University and the IRB at the Hospital for Special Surgery. We began by recording three instances of maximal pinch force in key and opposition pinch using a pinch meter (Model PG-30 pinch gauge, B&L Engineering, Tustin, CA) in self-selected wrist, elbow and shoulder postures.

Custom software running on a personal digital assistant (PDA) (Palm100 m, Palm, Inc., Santa Clara,

Table 1
Strength–dexterity scores for core region (Newtons)

Subject Group	Count	Pinch style					
		Opposition			Key		
		Mean	SD	CV(%)	Mean	SD	CV(%)
Unimpaired young adults	18	716	0	0	716.4	0	0
Unimpaired older adults	10	648	92	14	655.8	55	8
OA	14	504*	191	38	548.8*	190	35

*The osteoarthritis (OA) group is significantly different at $p<0.05$.
The coefficient of variation (CV) is (SD/mean)*100.

CA) randomized spring choice across pinch styles when collecting these readings. Key pinch was defined as holding the pinch meter (or spring) between the pad of the thumb and the radial aspect of the proximal interphalangeal joint of the forefinger. Opposition pinch was defined as holding the pinch meter (or spring) between the pad of the thumb and the pads of the fore- and middle-fingers. Participants were instructed, and the investigators verified, that no finger joint was hyperextended during pinch. We presented to each participant springs below their maximal pinch force at random to mitigate fatigue and learning effects, making the number of springs in the test more than 39 (see Results) and typically fewer than 72. The investigator entered the result of each attempted compression into the PDA and provided a 5 s rest between spring presentations. The session lasted at most 1 h, including obtaining informed consent. The S–D score for each pinch style was the sum of the strength values, in Newtons, of all successfully compressed springs. To quantify the repeatability of the S–D scores, 14 of the unimpaired young adults were tested twice within one week at the same time of the day.

The statistical test–retest analysis for repeatability compared the outcome of each spring in both sessions. We used a repeated measures, two-factor ANOVA to determine if the S–D scores and maximal pinch meter readings (dependent variables) were statistically different across the independent variables of pinch style and participant condition (unimpaired older adults vs. CMC OA patients).

3. Results

The repeatability analysis of the data showed that participants had the same results with each spring 96% and 94% of the time for key and opposition pinch, respectively.

A clear pattern emerged where every unimpaired young adult could compress all springs in a region of the grid bounded by *G* on the top and 9 on the right (Fig. 2), indicating the presence of a minimum region of performance for unimpaired young adults. We defined this subset of 39 springs as the *core region* of the S–D plane. Noting that not all older adults and OA participants could compress every spring in the core region, we compared their scores within that region.

For both pinch styles, the S–D scores inside the core region were significantly higher for the older adults than for the CMC OA participants ($p<0.05$; Table 1, Fig. 3). Pinch meter readings were not significantly different across subject groups for either pinch style (Table 2).

4. Discussion

Quantifying the dynamic interaction between the magnitude and directional control of finger forces can greatly improve our understanding of the sensorimotor control of the hand and the clinical evaluation of pinch performance (Valero-Cuevas et al., 1998; Valero-Cuevas, 2000b; Johanson et al., 2001). We studied key and opposition pinch because they are two modalities of manipulation essential to the activities of daily living that are often impaired by orthopaedic and neurological conditions (Eaton and Glickel, 1987; Lane, 1997; House et al., 1976; House, 1985).

We found the S–D score to be at least 94% reproducible. Moreover, the results in Tables 1 and 2 show that the S–D test distinguished between CMC OA participants and asymptomatic older adults ($p<0.05$), while maximal pinch strength from pinch meter readings did not. In the asymptomatic older adults, maximal pinch meter readings have a greater coefficient of variation than the S–D test. These results justify including the S–D test in future studies of the deterioration of dynamic pinch performance associated with CMC OA of the thumb.

Voluntary tests of motor performance are inherently susceptible to adaptive strategies that may mask impairment, or malingering that may simulate impairment. The S–D test may be less susceptible to adaptive strategies than pick-and-place tests because it quantifies directional control of fingertip forces in standardized pinch styles. Also, because the goal of the S–D test administered at random is not obvious, malingering may be detected by low repeatability or the subject failing at easy springs but succeeding at more difficult ones.

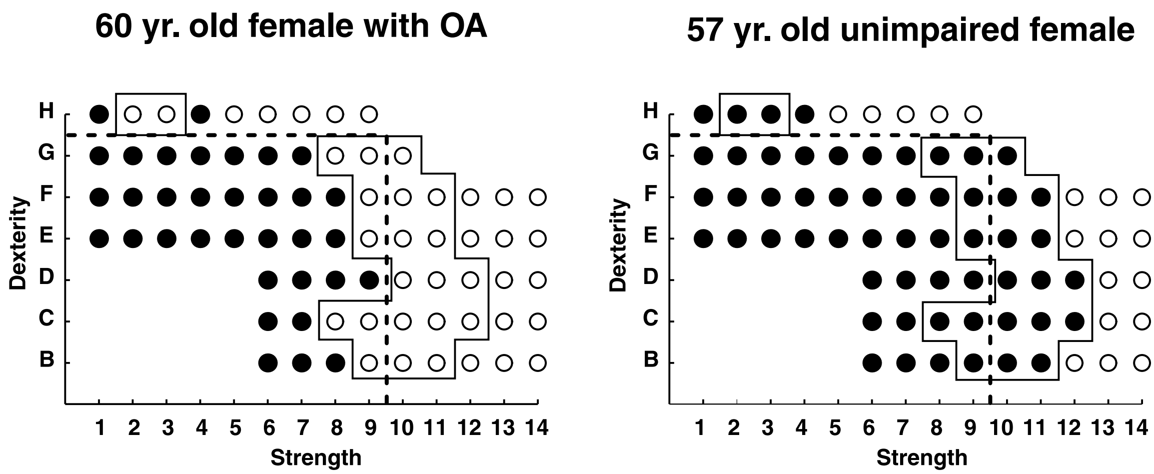

Fig. 3. Representative example of the graphical representations of the results of the S–D test from a 60 yr old female with CMC OA (left) and a 57 yr old unimpaired female (right). Springs that were successfully compressed to their solid length are shown as filled circles and those that were not are shown as open circles. The demarcated regions are those where the unimpaired participant could succeed while the participant with OA could not. The dashed line demarcates the core region (see Fig. 2), which indicates the performance for all unimpaired young adults.

Table 2
Pinch meter readings (Newtons)

Subject Group	Count	Pinch style					
		Opposition			Key		
		Mean	SD	CV(%)	Mean	SD	CV(%)
Unimpaired young adults	18	87.6	19.8	23	84.3	19.8	24
Unimpaired older adults	10	71.2	25.6	37	67.4	21.2	31
OA	14	54.3	17.1	31	57.6	19.8	34

There were no significant differences among subject groups.

The limitations of the S–D test include manufacturing tolerances and participant time burden. The higher the dexterity index, the greater its sensitivity to manufacturing tolerances becomes, and the greater the range in values for each row of the S–D plane when using off-the-shelf springs (see Fig. 2). Custom-wound springs would further improve the quality of the S–D test. Note, for example, that springs H2 and H3 were not compressed by the OA participant, even though springs H1 and H4 were (Fig. 3). Manufacturing tolerances of springs H2 and H3 could have give them a slightly higher dexterity index other springs in row H. Participant burden could be reduced in future studies because our results show the subset of 39 springs in the core region sufficed to distinguish older adults with and without CMC OA. Using the core springs would also reduce the likelihood of fatigue and have a participant time burden comparable to that of currently used tests (e.g. Jebsen–Taylor test).

The advantages of the S–D test include being a relatively inexpensive and simple method to quantify sensorimotor integration for dynamic pinch performance. By finding the limit of instability (i.e., spring buckling) the fingers can control at sub-maximal forces, the S–D test is informative of the maximal effectiveness of sensorimotor integration to dynamically regulate fingertip force magnitude and directional control. We propose that the S–D test also has the potential to quantify pinch impairment and compare treatment outcomes in many orthopedic and neurological afflictions that degrade dynamic manipulation.

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