Control of Fingertip Forces in Young and Older Adults Pressing against Fixed Low- and High-Friction Surfaces

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Introduction

Mobile computing devices (e.g., smartphones and tablets) that have low-friction surfaces require well-directed fingertip forces of sufficient and precise magnitudes for proper use. Although general impairments in manual dexterity are well-documented in older adults, it is unclear how these sensorimotor impairments influence the ability of older adults to dexterously manipulate fixed, low-friction surfaces in particular. Young and older adults produced maximal voluntary contractions (MVCs) and steady submaximal forces (2.5 and 10% MVC) with the fingertip of the index finger. A Teflon covered custom-molded splint was placed on the fingertip. A three-axis force sensor was covered with either Teflon or sandpaper to create low- and high-friction surfaces, respectively. Maximal downward forces (Fz) during the submaximal force-matching tasks were 2.45 times greater (p = .001) for older adults than in young adults, and reached a maximum when older adults pressed against the Teflon surface while receiving visual feedback. These age-associated changes in motor performance are explained, in part, by altered muscle activity from three hand muscles and out-of-plane forces. Quantifying the ability to produce steady fingertip forces against low-friction surfaces may be a better indicator of impairment and disability than the current practice of evaluating maximal forces with pinch meters. These age-associated impairments in dexterity while interacting with low-friction surfaces may limit the use of the current generation of computing interfaces by older adults.

Abstract

Mobile computing devices (e.g., smartphones and tablets) that have low-friction surfaces require well-directed fingertip forces of sufficient and precise magnitudes for proper use. Although general impairments in manual dexterity are well-documented in older adults, it is unclear how these sensorimotor impairments influence the ability of older adults to dexterously manipulate fixed, low-friction surfaces in particular. Young and older adults produced maximal voluntary contractions (MVCs) and steady submaximal forces (2.5 and 10% MVC) with the fingertip of the index finger. A Teflon covered custom-molded splint was placed on the fingertip. A three-axis force sensor was covered with either Teflon or sandpaper to create low- and high-friction surfaces, respectively. Maximal downward forces (Fz) during the submaximal force-matching tasks were 2.45 times greater (p = .001) for older adults than in young adults, and reached a maximum when older adults pressed against the Teflon surface while receiving visual feedback. These age-associated changes in motor performance are explained, in part, by altered muscle activity from three hand muscles and out-of-plane forces. Quantifying the ability to produce steady fingertip forces against low-friction surfaces may be a better indicator of impairment and disability than the current practice of evaluating maximal forces with pinch meters. These age-associated impairments in dexterity while interacting with low-friction surfaces may limit the use of the current generation of computing interfaces by older adults.

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performance would show greater impairments in older than young adults when pressing against low- vs. high-friction surfaces. Young and older adults pressed against low- and high-friction surfaces to investigate age-related changes in: 1) MVC force magnitude and direction, 2) submaximal force fluctuations in normal and tangential forces with and without visual feedback, and 3) electromyogram (EMG) activity from three hand muscles during the MVC and submaximal force-matching tasks.

Materials and Methods

Ethics statement

The experiments were approved by the Institutional Review Board at the University of Wisconsin-Milwaukee. The local ethics committee approved consent for subjects ranging in age from 18–40 years and 65–90 years. All participants gave their written formal consent before participating in the study.

Subjects

21 young (age: 21.4 ± 3.7 years; range, 19–33 years; 10 females) and 18 older (age: 72.3 ± 7.0 years; range, 65–87 years; 9 females), right-handed adults with no reported neuromuscular disorders or hand pathologies volunteered for the study.

Experimental arrangement and procedures

Subjects were seated with their right forearm strapped to a horizontal platform (69 cm high) with a vacuum foam pad (Versaform pillow, Tumble Forms, Dolgeville, NY) to immobilize the elbow and forearm. As in Keenan et al. [6], subjects grasped a horizontal dowel with all fingers and thumb, except for the index finger, which was free to press on a three-axis force sensor (Nano 17, ATI Industrial Automation, Apex, NC; Figure 1). Forces were sampled at 1000 Hz (Spike2; Cambridge Electronic Design, UK). A low-friction Teflon surface was attached to a round pedestal (2.5 cm diameter) mounted on the force sensor. The sensor plane was oriented horizontally with downward normal forces denoted \( F_z \), and with the transducer rotated so that the \( x \)- and \( y \)-axes were in the medial/lateral \( (F_x) \) and palmar/dorsal \( (F_y) \) directions, respectively [lateral, dorsal, and downward forces corresponded to +N values; Figure 1]. Sensor surface position and height were adjusted such that the index finger was in a neutral abduction posture, the distal phalanx of the index finger was perpendicular to the sensor surface, and the proximal phalanx of the index finger was parallel to the sensor surface. As in our previous work to create a low-friction interface between the finger and sensor [6], subjects wore a custom-molded cover (i.e., thermoplastic material with rubber mesh insert for comfort) on the fingertip, with a thin Teflon overdlying EMG electrodes (see [11] for experimental details) on the skin overlying first dorsal introsseous (FDI), extensor digitorum communis (EDC), and flexor digitorum superficialis (FDS). Briefly, bipolar electrode pairs (4-mm diameter, silver-silver chloride; 10 mm inter-electrode distance) were positioned on the skin 15 and 30 mm distal to the estimated location of the innervation zone and in line with muscle fiber direction. EMG signals were amplified (1K; Coulbourn Instruments, Whitehall, PA) and band-pass filtered (15–1 KHz) using an isolated bio-amplifier. To normalize EMG data during the force pressing tasks, subjects performed brief 3–5 s maximal contractions of the three hand muscles while the experimenter provided manual resistance to the index finger at the start and end of the experiment (see [11]).

Data analysis

For the MVC tasks, the primary dependent variable was the peak \( F_z \) produced during MVC trials against the low- and high-friction surfaces. Peak \( F_z \) values from the two MVC trials were averaged and compared across friction conditions and subject ages. In addition, corresponding values of \( F_x \) and \( F_y \) when \( F_z \) was maximal were calculated and compared across conditions.

For the submaximal forces, the coefficient of variation in \( F_z \) (CV = SD of \( F_z \)/mean \( F_z \) ×100) was calculated from 3.5–7.5 s during the epoch of visual feedback, and from 8.5–12.5 s during the epoch of no visual feedback. As commonly done (e.g., [12,13]), force output during those two epochs was detrended by removing the linear trend from the force data, as drift during the no visual feedback condition could influence force variability (e.g., see Fig. 1B). CV values from the two trials were averaged and compared across age groups, friction conditions, and visual feedback conditions. The standard deviation of \( F_x \) and \( F_y \) for both epochs was also calculated and compared across conditions. Additionally, normalized average full-wave rectified EMG amplitudes were calculated for all tasks. For MVC tasks, EMG amplitudes were calculated for 500 ms centered on the peak in \( F_z \).

For the submaximal steadiness tasks, EMG amplitudes were calculated for the 4 s epoch of vision and no vision.
Statistical analysis

For MVC tasks, six mixed between-within subjects ANOVAs were conducted separately for Fz, Fx, and Fy, and EMG amplitudes (FDI, EDC, and FDS) with repeated measures on friction condition, and with the between-subjects factor of age group. For submaximal force steadiness tasks, six mixed between-within subjects ANOVAs were conducted for the CV in Fz, the standard deviation of Fx and Fy, and EMG amplitudes (FDI, EDC, and FDS) with repeated measures on friction condition, force level, and visual feedback, and with between-subjects factor of age group. Alpha level for all statistical tests was $p < .05$. Significant interactions were followed by post-hoc analyses (t-test with Bonferroni corrections). Results are presented as mean ± SD in the text and standard error (SE) in the figures.

Results

MVC tasks

Peak Fz magnitudes decreased ($F_{1,37} = 19.55; p < .001$) by 15.0% for the low-friction Teflon condition compared with the high-friction sandpaper condition (31.22 ± 13.29 N and 36.71 ± 14.88 N, respectively; Figure 2A). There was no significant difference ($F_{1,37} = 2.34; p = .135$) across young and older adults (37.38 ± 18.47 N and 30.55 ± 19.95 N, respectively; Figure 2A) or on interaction
between age group and friction condition ($F_{1,37} = 0.05; p = .833$). For tangential forces during MVCs, although there was no change ($F_{1,37} = 3.87; p = .057$) in $F_x$ between low- and high-friction conditions (0.98±0.57 N and 0.28±1.73 N, respectively), $F_y$ was greater ($F_{1,37} = 6.80; p = .013$) and directed dorsally when producing MVC forces against the sandpaper surface (1.47±3.24 N) relative to the Teflon surface (0.09±1.46 N). There were no age group main effects ($p > .201$) or significant interactions ($p > .05$) for $F_x$ and $F_y$.

EMG amplitude in FDI decreased ($F_{1,37} = 4.58; p = .039$) during MVCs against Teflon relative to sandpaper, and increased ($F_{1,37} = 8.592; p = .006$) for older compared with young adults (Figure 2B); there was no significant interaction between age group and friction condition ($F_{1,37} = 1.68; p = .203$). In addition, the only other significant change in muscle activity during MVCs was that EMG amplitude in FDS decreased ($F_{1,37} = 6.15; p = .018$) during MVCs against Teflon relative to sandpaper (Figure 2B).

Sub maximal force-matching tasks

Figure 3 shows that the CV of force ($F_z$): 1) increased ($F_{1,37} = 23.06; p = .001$) in older compared with young adults, 2) increased ($F_{1,37} = 5.59; p = .023$) while pressing against Teflon relative to sandpaper, and 3) increased ($F_{1,37} = 14.9; p = .001$) while pressing with 2.5% vs. 10% peak $F_z$. There was also a significant age group by vision interaction ($F_{1,37} = 11.69; p = .002$) with the CV of $F_z$ for older adults increased ($p = .006$) for the vision compared with no vision condition, and the CV of $F_z$ for young adults decreased ($p = .05$) during the vision compared with no vision condition. There were no other significant interactions ($p > .001$) for the CV of $F_z$. Thus, fluctuations in $F_z$ were greatest when older subjects pressed against the low-friction surface at 2.5% peak $F_z$ with visual feedback (Figure 3).

Related to force fluctuations in tangential forces during sub maximal tasks, the SD of force magnitude in $F_x$ was increased ($F_{1,37} = 5.32; p = .027$) in older (0.036±0.025 N) relative to young subjects (0.023±0.023 N) and also increased ($F_{1,37} = 38.88; p = .001$) at the 10% peak $F_x$ (0.043±0.03 N) compared with the 2.5% peak $F_x$ level (0.015±0.008 N). However, the increase in SD of force with age in $F_x$ was qualified by an age group by vision interaction ($F_{1,37} = 5.26; p = .028$). Specifically, the SD of $F_x$ was increased ($p = .008$) in older relative to young adults when visual feedback was provided (0.037±0.026 N and 0.021±0.025 N, respectively), but not significantly different ($p = .108$; 0.034±0.026 N and 0.024±0.024 N, respectively) without visual feedback. There were no significant changes ($p > .189$) in $F_z$ during the submaximal force tasks. Thus, force fluctuations in $F_x$ and $F_z$ were not significantly different across the low- and high-friction conditions.

EMG amplitude in FDI (Figure 4A) during the submaximal tasks was: 1) increased ($F_{1,37} = 18.39; p = .001$) in older compared to younger adults, 2) increased ($F_{1,37} = 78.31; p < .001$) while pressing at 10% vs. 2.5% peak $F_x$, and 3) similar ($F_{1,37} = 0.5; p = .494$) for sandpaper and Teflon surfaces. EMG amplitude in EDC (Figure 4B) was increased ($F_{1,37} = 10.63; p = .002$) in older compared to young adults for the vision compared with no vision condition, and the CV of $F_z$ for young adults decreased ($p = .05$) during the vision compared with no vision condition (Figure 4C). All other main effects and interactions were not significant ($p > .07$).

Discussion

The key findings of the present study are as follows. First, submaximal force fluctuations were increased in older adults relative to young adults, especially for the condition that involved pressing against a fixed, low-friction surface with visual feedback at low force magnitudes. Second, impaired cutaneous sensation was not the primary factor influencing impaired motor performance in the older adults while pressing against the low- vs. high-friction surface as subjects wore a thermoplastic splint to ensure that cutaneous feedback was similar across the two friction conditions. Third, peak $F_x$ magnitudes decreased similarly for young and older adults while pressing against low- vs. high-friction surfaces. Fourth, EMG activation patterns across FDI, EDC, and FDS were altered while pressing against the low- vs. high-friction surface. Taken together, these findings are consistent with the concept that interacting with low-friction surfaces is challenging, especially for
Based on performance on MVC and submaximal tasks, quantifying the ability to produce submaximal finger-tip forces against low-friction surfaces may be a better indicator of impairment and disability than the common practice of evaluating stable forces with pinch grip meters. These results also likely indicate potential difficulties that older adults may encounter when trying to use computing interfaces that employ low-friction surfaces.

Steadiness of submaximal forces

The functional relevance of force fluctuations has been previously established in older adults [10,14]. In the current study, fluctuations in force magnitude were increased when older adults pressed at the 2.5% peak Fz level with visual feedback against the Teflon surface (Figure 3). Indeed, CV of force for this condition was 12.3±9.9%, which is more similar to that reported for stroke patients during fatiguing contractions [13] than healthy older adults where values typically range from 4–8% at low force levels [10,11]. Although the CV of force is generally greatest at low forces [11,13], especially when visual feedback is provided [13], force variability may have further increased in older adults pressing against Teflon due to: 1) an inability to stabilize the position of the finger and control variability in tangential forces.

Figure 3. Summary data for fluctuations in force during submaximal force-matching tasks. Fluctuations in downward forces (coefficient of variation in Fz) during submaximal force tasks were increased in older relative to young adults for both 2.5% (A) and 10% peak Fz (B) force-matching tasks, and while pressing against a low-friction relative to a high-friction surface. There was also an age by vision interaction (p = .002), with greater force fluctuations in older adults when vision was present, and lesser force fluctuations in young adults when vision was present. Values are means ± SE. *p < .001 vs. young adults; †p = .023 vs. high-friction; ‡p = .05 vs. vision in young adults; ‡‡p = .008 vs. vision in older adults.

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Figure 4. Summary data for electromyogram (EMG) activity during submaximal force-matching tasks. Olders adults had greater EMG activity than young adults for first dorsal interosseus (FDI) (A) and extensor digitorum communis (EDC) (B) while performing submaximal steadiness tasks. EMG activity also increased in EDC when pressing against a low-friction vs. high-friction surface, potentially to stabilize the fingertip while pressing against the slippery Teflon surface. In contrast to EDC, EMG amplitude also increased in FDI and flexor digitorum superficialis (FDS) while pressing at the 10% vs. 2.5% MVC force level. Thus, altered submaximal force fluctuations were accompanied by changes in muscle activation strategies by young and older adults. Values are means ± SE. *p < .001 vs. young adults; †p = .001 vs. 2.5 MVC force; ‡p = .002 vs. young adults; ‡‡p = .006 vs. high-friction surface.

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First, a number of approaches consider variability as efficient motor control (e.g., ‘uncontrolled manifold’ [16] and ‘minimum intervention’ [17] hypotheses). In these approaches, the sensorimotor system preferentially controls task-relevant parameters while allowing task-irrelevant parameters to fluctuate. In the current study, variability in $F_z$ is explicitly the task-relevant parameter, while the task relevance of variability in $F_x$ and $F_y$ depends on friction condition. Specifically, fine control of tangential forces is critical when pressing against a low-friction surface to prevent slipping [17], though not as important when pressing against sandpaper. Thus, by changing the friction condition the nature of the task and the task-relevant parameters are also changed, placing greater demands on the central nervous system and potentially resulting in concomitant increases in the CV of normal forces as the task becomes more challenging. Consistent with this interpretation, Shinohara et al. [18] analyzed the covariation of force within the ‘uncontrolled manifold’ and found that young adults better stabilized force than older adults when pressing with the fingers against a stable manipulandum. In addition, the submaximal tasks performed in the current study were certainly challenging for older adults. Specifically, in older relative to young adults force fluctuations in the dorsal/palmar direction increased by 56.5% and EMG activity in FDI and EDC increased by 310% and 191%, respectively. Interestingly, there were no significant differences in tangential force fluctuations between sandpaper and Teflon surfaces in the current study, though EDC EMG activity increased when pressing against Teflon relative to sandpaper surfaces, potentially to help stabilize the finger against the slippery Teflon surface. Nonetheless, pressing against sandpaper and Teflon surfaces may not be different enough to highlight the difference in tangential force fluctuations. One possibility that could address this limitation in future work is to rigidly fix the fingertip to the target surface, thereby making the control of tangential forces unnecessary, in contrast to the sandpaper condition used in the current study.

Second, in addition to vision, other sensory modalities (e.g., cutaneous sensation and proprioception) are impaired in older adults (e.g., [2,3]) and may influence steady force production against low-friction surfaces. For example, cutaneous sensation is impaired in older adults and influences slip-grip responses [3]. Partly for this reason, we used a thermoplastic finger splint so that cutaneous sensation did not vary across friction conditions. However, by minimizing cutaneous sensation with the finger splint, other impaired sensory modalities (e.g., proprioception and vision) could be more heavily relied upon and similarly impair performance. In addition, visual feedback in the current study was of fingertip force magnitude, not visual feedback of motion as is frequently employed during activities of daily living. Given the differences between our experimental approach and more ecological tasks, further mechanistic studies are needed to examine the role of impaired sensation in older adults to influence manipulation of low-friction surfaces.

**MVC forces**

Peak $F_z$ forces were statistically similar ($p = .135$) in young and older adults and the $\sim 15.0\%$ decrease ($p < .001$) in peak $F_x$ force while pressing against Teflon compared with sandpaper surfaces was similar across age groups (Figure 2A). Similarly, Seo et al. [4] found a 10% decrease in pinch grip force in young subjects pressing against a low-friction paper surface compared to a high-friction rubber surface. Interestingly, the decrease in peak $F_z$ across friction surfaces in the current study was independent of subject age, suggesting that the low-friction surface was not more problematic for older relative to young adults, at least while producing maximal forces. Also, the 15.0% decrease in peak $F_z$ was accompanied by a 9.8% and 16.1% decline in FDI and FDS EMG amplitudes (Figure 2B), respectively. Therefore, the reduction in peak $F_z$ across friction conditions may be a voluntary response to limit forces against the slippery Teflon surface. Alternatively, fingertip forces were directed dorsally relative to the normal force by $2.1^\circ$ vs. $0.13^\circ$ while pressing against sandpaper and Teflon, respectively. As discussed in Valero-Cuevas et al. [19], the change in fingertip force direction across friction conditions could have resulted in a change in the activation pattern across the seven muscles of the index finger to maximize force. Nonetheless, the current study was limited to examine EMG from only three muscles. Lastly, FDI EMG amplitude increased ($p = .006$) by 42.3% in older compared to young adults (Figure 2B). As older adults may experience a preferential weakening of intrinsic vs. extrinsic hand muscles [9,20], this increased activity in FDI, an intrinsic hand muscle, could be a compensatory response to account for the decreased muscle strength of the intrinsic hand muscles.

**Conclusion**

Maximum pinch grip is commonly evaluated clinically in older adults, though it may not be the most sensitive measure available to assess hand function. For example, in the current study older subjects produced similar ($p = .135$) maximal force magnitudes as young adults, but submaximal force fluctuations were 3.7× greater in older adults relative to young adults pressing against the low-friction surface with visual feedback. Thus, motor tasks that demand precision in directing fingertip forces may be a more sensitive metric to assess motor function in older adults. For example, the Strength-Dexterity test assesses the capacity to accurately direct pinch forces by pressing and compressing different springs [7], and older adults had impairments relative to young adults in their ability to accurately direct forces. The current study extends that result and finds that motor performance is also impaired when well-directed forces on fixed, low-friction surfaces are required. Also, although we did not directly assess the ability of older adults to manipulate low-friction computing interfaces, the results of this study may be pertinent. Specifically, interacting with the low-friction surfaces in these devices requires older adults to produce steady, accurate, and well-directed forces at low forces with visual feedback guiding performance, a similar set of conditions that older adults struggled with in the current study. Thus, future work should explore the potential limitations older adults may have interacting with mobile computing devices and develop ergonomic aids and training interventions to improve performance.

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**Author Contributions**

Conceived and designed the experiments: KGK WVM. Performed the experiments: KGK WVM. Analyzed the data: KGK WVM. Wrote the paper: KGK WVM.
References

1. Falconer J, Hughes SL, Naughton BJ, Singer R, Chang RW, et al. (1991) Self-report and performance-based hand function tests as correlates of dependency in the elderly. J Am Geriatr Soc 39: 695–699.

2. Johansson RS (1996) Sensory control of dexterous manipulations in humans. In: Haggard P JF, & Wing A., editor. Hand and brain. San Diego: Academic. 381–414.

3. Cole KJ, Rotella DL, Harper JG (1999) Mechanisms for age-related changes of fingertip forces during precision gripping and lifting in adults. J Neurosci 19: 3238–3247.

4. Seo NJ, Shim JK, Engel AK, Enderes LR (2011) Grip surface affects maximum pinch force. Hum Factors 53: 740–748.

5. Johanson ME, Valero-Cuevas FJ, Heuts VR (2001) Activation patterns of the thumb muscles during stable and unstable pinch tasks. J Hand Surg [Am] 26: 698–705.

6. Keenan KG, Santos VJ, Venkadesan M, Valero-Cuevas FJ (2009) Maximal voluntary fingertip force production is not limited by movement speed in combined motion and force tasks. J Neurosci 29: 8764–8789.

7. Valero-Cuevas FJ, Smaby N, Venkadesan M, Peterson M, Wright T (2003) The strength-dexterity test as a measure of dynamic pinch performance. J Biomech 36: 265–270.

8. Cole KJ (2006) Age-related directional bias of fingertip force. Exp Brain Res 175: 285–291.

9. Kapur S, Zatsiorsky VM, Latash ML (2010) Age-related changes in the control of finger force vectors. J Appl Physiol 109: 1827–1841.

10. Marmon AR, Pascoe MA, Schwartz RS, Enoka RM (2011) Associations among strength, steadiness, and hand function across the adult life span. Med Sci Sports Exerc 43: 560–567.

11. Keenan KG, Massey WV, Walters TJ, Collins JD (2012) Sensitivity of EMG-EMG coherence to detect the common oscillatory drive to hand muscles in young and older adults. J Neurophysiol 107: 2086–2095.

12. Baweja HS, Patel BK, Martinowitz JD, Vu J, Christou IA (2009) Removal of visual feedback alters muscle activity and reduces force variability during constant isometric contractions. Exp Brain Res 197: 35–47.

13. Tracy BL, Dicenso DV, Jorgenson B, Welsh SJ (2007) Aging, visuomotor correction, and force fluctuations in large muscles. Med Sci Sports Exerc 39: 469–479.

14. Marmon AR, Gould JR, Enoka RM (2011) Practicing a functional task improves steadiness with hand muscles in older adults. Med Sci Sports Exerc 43: 1531–1537.

15. Hyngstrom AS, Ounshko T, Heitz RP, Rutkowski A, Hunter SK, et al. (2012) Stroke-related changes in neuromuscular fatigue of the hip flexors and functional implications. Am J Phys Med Rehabil 91: 33–42.

16. Scholz JP, Schoner G (1999) The uncontrolled manifold concept: identifying control variables for a functional task. Exp Brain Res 126: 289–306.

17. Valero-Cuevas FJ, Venkadesan M, Todoreov E (2009) Structured variability of muscle activations supports the minimal intervention principle of motor control. J Neurophysiol 102: 59–68.

18. Shinohara M, Scholz JP, Zatsiorsky VM, Latash ML (2004) Finger interaction during accurate multi-finger force production tasks in young and elderly persons. Exp Brain Res 156: 282–292.

19. Valero-Cuevas FJ, Jazae FE, Burgess CG (1998) Large index-fingertip forces are produced by subject-independent patterns of muscle excitation. J Biomech 31: 693–703.

20. Shinohara M, Latash ML, Zatsiorsky VM (2003) Age effects on force produced by intrinsic and extrinsic hand muscles and finger interaction during MVC tasks. J Appl Physiol 95: 1361–1369.