Applied Ergonomics 52 (2016) 24–28

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Two-handed grip on a mobile phone affords greater thumb motor performance, decreased variability, and a more extended thumb posture than a one-handed grip

Matthieu B. Trudeau [a], Deanna S. Asakawa [b, *], Devin L. Jindrich [b], Jack T. Dennerlein [c, d]

[a] University of Calgary, Calgary, AB, Canada
[b] California State University, San Marcos, CA, USA
[c] Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA
[d] Bouvé College of Health Sciences, Northeastern University, MA, USA

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form
12 June 2015
Accepted 23 June 2015
Available online 7 July 2015

Keywords:
Mobile computing
Fitts' law
Repetitive stress

ABSTRACT

Holding a mobile computing device with two hands may affect thumb motor performance, joint postures, and device stability compared to holding the device and tapping the touchscreen with the thumb of the holding hand. We tested the hypotheses that holding a touchscreen mobile phone with two hands lead to increased thumb motor performance, different thumb postures, and decreased device movement relative to using one hand. Ten right-handed participants completed reciprocal thumb tapping tasks between emulated keys on a smartphone in either a one- (portrait) or two-handed (landscape) grip configuration. Effective index of performance measured from Fitts' Law was 9% greater ($p < 0.001$), movement time 7% faster ($p < 0.001$), and taps were 4% more precise ($p < 0.016$) for the two-handed grip. Tapping with a two-handed grip involved significantly different wrist and thumb postures than a one-handed grip. Variability of the computing device's movement was 36–63% lower for the two-handed grip compared to the one-handed grip condition ($p < 0.001$). The support for our hypotheses suggests that a two-handed grip results in increased performance and more extended wrist and thumb postures than a single-handed grip. Device designs that allow two-handed grips may afford increased performance relative to a one-handed grip.

1. Introduction

Recent surveys estimate that 45% of Americans own a smartphone (Duggan and Rainie, 2012), and that users spend an average of 4.7 h/day using hand-held mobile device(s) (Berolo et al., 2011). Several postures are commonly selected to interact with mobile devices, with over half of users preferring to use their thumbs (Gold et al., 2012). However, little is known about the effect of different interaction techniques on performance and posture.

Previous studies reporting thumb posture, thumb performance, and muscle activity during mobile device use have revealed that device design could affect both user performance and musculoskeletal strain (Jonsson et al., 2007, 2011; Karlson et al., 2008; Gustafsson et al., 2010; Hogg, 2010; Trudeau et al., 2012b). For right-handed users, tapping on the top right or bottom left of a touchscreen was associated with the greatest performance compared with other areas on the screen, as indicated by shorter transition times, better accuracy and fewer errors (Park and Han, 2010a, 2010b). Greater performance is associated with postures involving moderate thumb flexion or extension (Trudeau et al., 2012b), and small devices (Trudeau et al., 2012a).

The grip that a user selects could affect motor performance and musculoskeletal strain (Gustafsson et al., 2011). Performance and strain could be related to hand size relative to the device, comfort, multitasking needs, accuracy requirements, need for support, or maintaining stability. Simultaneously supporting a device and tapping on its touchscreen using a single hand may be more difficult than using a two-handed grip, where task requirements can be shared. For example, if the thumb is involved in device stability but is also used to tap, then these two functions may conflict, therefore decreasing performance. Moreover, a single-handed grip may

* Corresponding author. Department of Kinesiology, California State University, San Marcos, 333 S. Twin Oaks Valley Rd., University Hall 302, San Marcos, CA 92096, USA.
E-mail address: dasakawa@csusm.edu (D.S. Asakawa).

http://dx.doi.org/10.1016/j.apergo.2015.06.025
0003-6870/

constrain thumb movement and require sub-optimal postures. Potentially for these reasons, Gustafsson et al. (2011) found that 62% of participants held mobile phones using a two-handed grip that involved less extensor digitorum muscle activity than a single-handed grip. However, whether the preference for a two-handed grip reflects a choice based on motor performance, posture, device stability, or other factors is unknown.

The purpose of this study was to determine if holding a mobile phone-sized computing device with one or two hands affects thumb function during tapping tasks. Specifically, we tested the hypothesis that a two-handed grip leads to increased thumb motor performance, different thumb joint postures, and decreased device movement relative to a one-handed grip.

2. Material and methods

2.1. Participants and tasks

We studied unimpaired right-handed participants (5 male, 5 female) with mean (±SD) age of 27.0 ± 7.0 yrs and hand length of 18.7 ± 1.7 cm. The equal number of male and female participants provided within subject comparisons that were balanced across two genders. We obtained informed written consent from all participants using a protocol approved by The Harvard School of Public Health Office of Human Research Administration. Participants held an iPhone 3® (Apple Inc., Cupertino, CA) that measured 4.5 × 2.4 × 0.48 inches and weighed 4.8 oz. The one-handed grip involved holding the device in the portrait orientation with the right hand, whereas a two-handed grip involved holding the device with both hands in the landscape orientation (Fig. 1). The task involved reciprocal tapping between two of twelve emulated keys as fast and accurately as possible, which is a requirement for applying a Fitts' Law model to measure effective performance (Douglas et al., 1999). For each task, the participant was provided practice time that consisted of approximately 2–3 s of reciprocal tapping for each task. More practice was provided to the participant if they desired. Once the participant verbally indicated that they were accustomed to the tapping task, 6 s of data were collected. Sampling time was selected to allow at least 8 taps on each key, thus affording the variability required for the calculation of Fitt's Law effective performance. Participants rested for 90 s after every 15 trials. The rest duration and frequency were determined through pilot testing as appropriate time periods to minimize any confounding effects of fatigue.

The presentation of key pairs within each grip condition was randomized to represent all incoming tap directions for each key. The average (±SE) number of trials analyzed per participant was 47 ± 6 trials for the one-handed grip configuration and 32 ± 6 trials for the two-handed grip configuration. All trials were performed sequentially within each grip condition. Between trials, participants could adjust their grip. All the emulated keys were included for the one-handed condition, whereas the left-most column of keys was not included for the two-handed condition to better represent actual usage in which the left thumb could reach these keys. For the two-handed grip condition, participants were instructed to simulate the grip they would use if they were typing using both thumbs. To reinforce this instruction, participants performed reciprocal tapping tasks with the left thumb every 7 trials even though no data were collected for these trials. Although the keys for several current smartphones change depending on the device's orientation, we kept the key size consistent across orientation conditions for consistency and to reduce confounding effects of target size. The calculation of effective performance from Fitts' Law considered the effective target width that was accomplished by the participant, as described in Section 2.3.

2.2. Kinematic measurements

An active-marker motion capture system (Optotrak Certus; Northern Digital Inc., Waterloo, Canada) recorded the 3D kinematics of the device, the right forearm, hand and thumb. Rigid plates holding sets of three infrared light emitting diodes (IREDs) were placed on the phone, the proximal phalange of the thumb, the dorsal surface of the hand, and the forearm (Fig. 1). Two additional IREDs were affixed to the thumb nail. The IRED placements minimized physical and visual obstructions for the participant while incorporating established methods for measuring thumb kinematics (Kuo et al., 2002, 2003; Li and Tang, 2007) and accounting for the degrees of freedom of each joint (Cooney et al., 1981; Hollister et al., 1995). Data were collected at 100 Hz, and digitally filtered through a low-pass, fourth-order Butterworth filter with a 10 Hz cutoff frequency. Bony landmarks were digitized and used to transform the IRED orientations to describe the anatomical segment location and orientation, and the joint center locations (Winter, 2005).

Joint angles were calculated relative to a reference posture with the forearm, hand and fingers aligned, and the thumb held straight along the palm such that it was pronated 90° relative to the index finger to align the long axes of the first metacarpal and the trapezium (Cooney et al., 1981). Right wrist and thumb joint angles were computed from the Euler angles of the rotation matrices describing the orientation of the joint's distal segment relative to the proximal segment (Winter, 2005).

The completion of a thumb tap was defined as the instant when the vertical (Z) position of the thumb's most distal IRED relative to the phone's surface reached a local minimum, with respect to time, with a relative horizontal position within a 1.5 cm square area

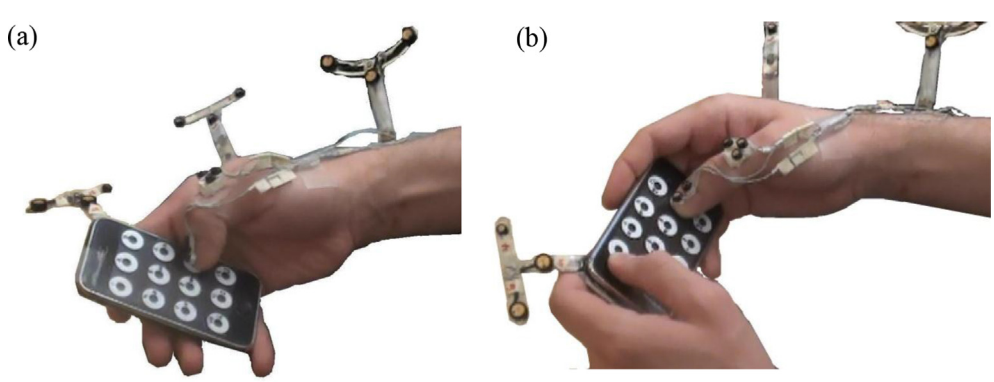

Fig. 1. (a) Single-handed grip configuration, and (b) two-handed grip configuration.

about the center of the target key. The horizontal distance and movement time from the previous tap, and the position of the thumb's distal IRED, were identified for each tap. Wrist joint and thumb angles were also calculated at the instant of tap completion.

Device movement variation was calculated as the standard deviation of the phone's inclination about all three axes of rotation (X-pitch, Y-roll, Z-yaw) within a trial (Fig. 2). The standard deviations were averaged across trials within each grip condition to determine the average phone movement variation for each axis within each condition.

2.3. Thumb motor performance measurements

The effective index of performance was calculated as $IP_e = IDe/MT$, where MT is the average movement time and IDe is effective index of difficulty (Fitts, 1954; Douglas et al., 1999; Soukoreff and MacKenzie, 2004; Wobbrock et al., 2008). IDe was calculated as $IDe = \log 2\,(Ae/We + 1)$, where Ae is the horizontal distance between the keys involved in the trial. The effective target width is given as $We = 4.133 * SD$. SD is the standard deviation of the thumb tip IRED horizontal (X, Y plane) position on the touchscreen device surface about the mean horizontal position for all taps on a specific key during the trial. Use of the effective target width provided an indication of a user's precision relative to each key location, with larger effective widths corresponding to less precise key locations. An effective index of performance (IP_e) was calculated for each key within a trial based on an across tap average movement time and distance.

2.4. Statistical analyses

The variables IP_e, We, MT, thumb joint angles, wrist joint angle, and phone movement variation, were calculated and averaged across trials within each grip condition for every participant. We used a mixed-effects analysis of variance (ANOVA), with participant as the random effect and grip condition as the fixed effect, to test for significant differences in thumb motor performance, joint postures and phone movement (JMP; SAS Institute, Cary, NC).

3. Results

Effective indices of performance (IP_e) were 9% greater ($p < 0.001$) for the two-handed grip compared to the one-handed grip (Table 1). Movement time for completing the tapping tasks was 7%, 20 msec, faster ($p < 0.001$), and taps were 4% more precise (i.e., smaller We) for the two-handed grip condition (Table 1). All three performance measures support the hypothesis that the two-handed grip is associated with greater motor performance.

Using a two-handed grip resulted in significantly more extended wrist and thumb joint postures than using a one-handed grip (Table 2). A two-handed grip involved 5°(50%) more wrist extension ($p < 0.001$). The thumb CMC joint was significantly more extended (5°), abducted (3°), and supinated (8°) for the two-handed compared to the one-handed grip condition ($p < 0.001$). The thumb metacarpophalangeal (MCP) joint was 2° (50%) more extended ($p < 0.001$) during the two-handed compared to the one-handed grip condition. The significant differences in a majority of joint angles support the hypothesis that a two-handed grip involves significant joint posture changes relative to a one-handed grip.

Phone movement variation was 36–63% (0.9°– 2.1°) lower across all three axes for the two-handed grip condition compared to the one-handed grip condition ($p < 0.001$, Table 3), supporting the hypothesis that a two-handed grip involves less device movement than a one-handed grip.

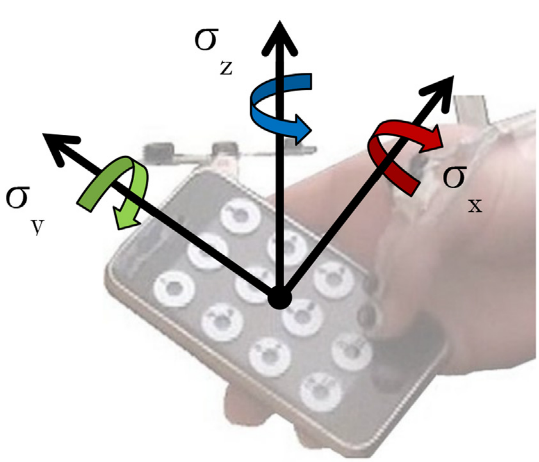

Fig. 2. Orientation of the phone's coordinate system used for the calculation of phone movement variation. Phone movement variation was calculated as the standard deviation of the phone's inclination about the X, Y, and Z axes. The phone coordinate system's orientation is similar across both grip conditions: the X axis pointing laterally, the Z axis normal to the phone's surface, and the Y axis pointing up orthogonal to the X and Z axes.

4. Discussion

This study's aim was to compare thumb motor performance and thumb, wrist, and smartphone kinematics between two-handed and single-handed grips. The results support our hypotheses that holding a mobile computing device with a two-handed grip results in greater thumb motor performance, different wrist and thumb postures, and decreased device movement relative to a one-handed grip.

The result of greater performance for the two-handed compared to the one-handed grip may be due to the fact that the two-handed grip effectively uncouples two aspects of the motor task: holding the device and tapping on the screen. Uncoupling support and tapping may allow for cooperation between the hands (Haaland et al., 2012). Cooperation could involve functional specialization of the hands, and could explain the improvements in both tapping performance (Table 1) and stability that we found for the two-handed grip compared to the one handed grip (Table 3; Sainburg et al., 2013). A two-handed grip may thus be preferable for tasks in which a user's thumb performance (i.e., speed and precision) is of the essence, such as gaming or typing an email.

Use of a two-handed grip resulted in a more extended wrist and thumb compared to the one-handed grip. Based on previous findings, we expected the interphalangeal (IP) joint of the thumb to be more extended for the two-handed grip (Trudeau et al., 2012b). However, we found that participants did not extend the IP joint during two-handed tapping. Instead, participants adjusted thumb flexion at both the CMC and MCP joints, suggesting a more general strategy of using proximal joints to modify posture (Yao et al., 2012). We speculate that the increased use of the thumb's proximal degrees of freedom (i.e., CMC and MCP joints) rather than the IP joint, and the less extended posture of the wrist, may represent a preferred posture for the user. Further studies should assess whether the increased use of the thumb's proximal degrees of freedom relative to the distal joint is associated with a reduced incidence of musculoskeletal disorders such as osteoarthritis and tendinitis, as several case studies have been reported in relation to the use of mobile devices (Menz, 2005; Ming et al., 2006; Storr et al., 2007; Ciccarelli et al., 2015; Ashurst et al., 2010).

There were limitations to this study. First, reciprocal tapping tasks between set locations on the touchscreen are not a complete representation of thumb motion during tasks such as typing or web

Table 1
Across participant mean (and standard error) values for Fitts' performance metrics for each grip condition.

Grip condition	Motor performance, IP_e (bits/sec)[b]	Movement time, MT (msec)[c]	Precision, W_e (mm)[c]
One-handed	12.1 (0.5)	281 (15)	4.6 (0.2)
Two-handed	13.2 (0.5)	261 (15)	4.4 (0.2)
p-value[a]	**<0.001**	**<0.001**	**0.016**

[a] Statistically significant ANOVA results are in bold.
[b] Larger values indicate better performance.
[c] Smaller values indicate better performance.

Table 2
Least square mean (and standard error) values for joint angles (°) for both grip conditions. Joint angles were expressed relative to a reference posture where the forearm, hand and fingers were aligned, and the thumb was held straight along the palm such that it was pronated by 90° relative to the index finger, with the wrist straight. Flexion, abduction and supination are positive, whereas extension, adduction and pronation are negative.

Grip condition	Wrist		CMC			MCP		IP
	Extension (°)	Abduction (°)	Extension (°)	Abduction (°)	Supination (°)	Extension (°)	Abduction (°)	Flexion (°)
One-handed	10 (3)	−18 (2)	0 (3)	24 (1)	−8 (7)	4 (3)	−11 (2)	37 (5)
Two-handed	15 (3)	−18 (2)	5 (3)	27 (2)	0 (7)	6 (3)	−11 (2)	37 (5)
p-value	**<0.001**	0.432	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.067	0.526

Statistically significant ANOVA results ($p < 0.05$) are in bold.

Table 3
Least squared mean (and standard error) values for the standard deviation of the phone's inclination about all three axes of rotation (X-pitch, Y-roll, Z-yaw) within a trial for each grip condition.

Grip condition	σ_x (°)	σ_y (°)	σ_z (°)
One-handed	2.5 (0.2)	2.8 (0.3)	3.3 (0.3)
Two-handed	1.6 (0.2)	1.5 (0.3)	1.2 (0.3)
p-value	**<0.001**	**<0.001**	**<0.001**

Statistically significant ANOVA results ($p < 0.05$) are in bold.

browsing. We selected a tapping task for several reasons. First, it allowed measurement of thumb motor performance across the functional area of the touchscreen in each grip using Fitts' Law. Second, tapping constitutes a subtask of typing, and thus performance for taps at specific locations on the screen can be used to predict the performance for more complex tasks. A predictive evaluation model can thus be developed for small mobile device keyboard designs to determine which design may lead to better performance, as shown by Trudeau et al. (2014). Third, simple tapping tasks are important as they are commonly used in gaming, selecting applications or dialing on a number pad. A second limitation was that we did not collect data with the device in a portrait orientation for a two-handed grip. We assumed that most users generally rotate the rectangular computing device to the landscape mode for a two-handed grip. In addition, while we saw significant within subject results, our small sample size did not allow enough statistical power for us to test for differences between subject characteristics such as gender. Others have reported no significant differences between genders in observational studies of trunk, upper arm, forearm, or wrist postures of the typing side in large subject populations (e.g. Gold et al., 2012). Finally, we did not examine tapping with the non-dominant hand. Future experiments will be necessary to determine whether dominance affects motor performance or grip preference.

In conclusion, one- and two-handed grips had significantly different thumb motor performance, device movement, and joint postures during tapping tasks on a mobile computing device. These findings suggest that device designs that allow two-handed grips may enable users to increase performance relative to a one-handed grip. Encouraging users to employ two-handed grips through hardware or software design may increase performance and reduce musculoskeletal strain during mobile device use relative to a one-handed grip.

Acknowledgments

This study was funded in part by the National Science Foundation (0964220), and the National Institute for Occupational Safety and Health (R01 OH008373). The authors thank the Office Ergonomics Research Committee for their additional support.

References

Ashurst, J.V., Turco, D.A., Lieb, B.E., 2010. Tenosynovitis caused by texting: an emerging disease. J. Am. Osteopath. Assoc. 110 (5), 294–296.
Berolo, S., Wells, R.P., Amick III, B.C., 2011. Musculoskeletal symptoms among mobile hand-held device users and their relationship to device use: a preliminary study in a Canadian university population. Appl. Ergon. 42, 371–378.
Ciccarelli, M., Chen, J.D., Vaz, S., Cordier, R., Falkmer, T., 2015. Managing children's postural risk when using mobile technology at home: challenges and strategies. Appl. Ergon. 51, 189–198.
Cooney 3rd, W.P., Lucca, M.J., Chao, E.Y., Linscheid, R.L., 1981. The kinesiology of the thumb trapeziometacarpal joint. J. Bone Jt. Surg. Am. 63, 1371–1381.
Douglas, S.A., Kirkpatrick, A.E., Mackenzie, I.S., 1999. Testing Pointing Device Performance and User Assessment with ISO 9241, Part 9 Standard. American Society of Mechanical Engineers, New York, p. 215.
Duggan, M., Rainie, L., 2012. Cell Phone Activities 2012. Pew Research Center's Internet & American Life Project. http://pewinternet.org/Reports/2012/Cell-Activities.aspx.
Fitts, P.M., 1954. The information capacity of the human motor system in controlling the amplitude of movement. J. Exp. Psychol. 47, 381–391.
Gold, J.E., Driban, J.B., Thomas, N., Chakravarty, T., Channell, V., Komaroff, E., 2012. Postures, typing strategies, and gender differences in mobile device usage: an observational study. Appl. Ergon. 43 (2), 408–412.
Gustafsson, E., Johnson, P.W., Hagberg, M., 2010. Thumb postures and physical loads during Mobile phone use – a comparison of adults with and without musculoskeletal symptoms. J. Electromyogr. Kinesiol. 20, 127–135.
Gustafsson, E., Johnson, P.W., Lindegård, A., Hagberg, M., 2011. Technique, muscle activity and kinematic differences in young adults texting on mobile phones. Ergonomics 54 (5), 477–487.
Haaland, K.Y., Mutha, P.K., Rinehart, J.K., Daniels, M., Cushnyr, B., Adair, J.C., 2012. Relationship between arm usage and instrumental activities of daily living after unilateral stroke. Archives Phys. Med. Rehabil. 93 (11), 1957–1962.
Hogg, N.A., 2010. Design of Thumb Keyboards: Performance, Effort and Kinematics. Master in Science Thesis. University of Waterloo, Waterloo, Canada, p. 69.
Hollister, A., Giurintano, D.J., Buford, W.L., Myers, L.M., Novick, A., 1995. The axes of rotation of the thumb interphalangeal and metacarpophalangeal joints. Clin. Orthop. Relat. Res. 320, 188–193.
Jonsson, P., Johnson, P.W., Hagberg, M., 2007. Accuracy and feasibility of using an electrogoniometer for measuring simple thumb movements. Ergonomics 50 (5), 647–659.

Jonsson, P., Johnson, P.W., Hagsberg, M., Forsman, M., 2011. Thumb joint movement and muscular activity during mobile phone texting – a methodological study. J. Electromyogr. Kinesiol. 21 (2), 363–370.
Karlson, A.K., Bederson, B.B., Contreras-Vidal, J.L., 2008. Understanding one-handed use of mobile devices. In: Lumsden, J. (Ed.), Handbook of Research on User Interface Design and Evaluation for Mobile Technology. National Research Council of Canada Institute for Information Technology, Hershey, PA, USA. PA, pp. 86–101.
Kuo, L.C., Cooney 3rd, W.P., Oyama, M., Kaufman, K.R., Su, F.C., An, K.N., 2003. Feasibility of using surface markers for assessing motion of the thumb trapeziometacarpal joint. Clin. Biomech. (Bristol, Avon) 18, 558–563.
Kuo, L.C., Su, F.C., Chiu, H.Y., Yu, C.Y., 2002. Feasibility of using a video-based motion analysis system for measuring thumb kinematics. J. Biomech. 35, 1499–1506.
Li, Z.M., Tang, J., 2007. Coordination of thumb joints during opposition. J. Biomech. 40, 502–510.
Menz, R.J., 2005. "Texting" tendinitis. Med. J. Aust. 182 (6), 308.
Ming, Z., Pietikainen, S., Hanninen, O., 2006. Excessive texting in pathophysiology of first carpometacarpal joint arthritis. Pathophysiology 13 (4), 269–270.
Park, Y.S., Han, S.H., 2010a. Touch key design for one-handed thumb interaction with a mobile phone: effects of touch key size and touch key location. Int. J. Ind. Ergon. 40, 68–76.
Park, Y.S., Han, S.H., 2010b. One-handed thumb interaction of mobile devices from the input accuracy perspective. Int. J. Ind. Ergon. 40, 746–756.
Sainburg, R.L., Good, D., Przybyla1, A., 2013. Bilateral synergy: a framework for Post-Stroke rehabilitation. J. Neurol. Transl. Neurosci. 1, 3.
Soukoreff, R.W., Mackenzie, I.S., 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. Int. J. Human Comput. Stud. 61, 751–789.
Storr, E.F., de Vere Beavis, F.O., Stringer, M.D., 2007. Texting tenosynovitis. N. Z. Med. J. 120 (1267), U2868.
Trudeau, M.B., Udtamadilok, T., Karlson, A.K., Dennerlein, J.T., 2012a. Thumb motor performance varies by movement orientation, direction, and device size during single-handed Mobile phone use. Hum. Factors Ergon. 54, 52–59.
Trudeau, M.B., Young, J.G., Jindrich, D.L., Dennerlein, J.T., 2012b. Thumb motor performance varies with thumb and wrist posture during single-handed mobile phone use. J. Biomech. 45, 2349–2354.
Trudeau, M.B., Sunderland, E.M., Jindrich, D.L., Dennerlein, J.T., 2014. A data-driven design evaluation tool for handheld device soft keyboards. PLos One 9, 9.
Winter, D.A., 2005. Biomechanics and Motor Control of Human Movement, third ed. Wiley, Hoboken, NJ.
Wobbrock, J.O., Myers, B.A., Aung, H.H., 2008. The performance of hand postures in front- and back-of-device interaction for mobile computing. Int. J. Human Comput. Stud. 66, 857–875.
Yao, J., Park, M.J., Davis, D., Chang, J., 2012. Ideal position for thumb interphanlangeal arthrodesis in the era of smartphones and text communication. Orthopedics 35 (11), 955–957.