Gesture Input for Users with Motor Impairments on Touchscreens: Empirical Results based on the Kinematic Theory

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Abstract
We capitalize in this work on the motor performance criteria of the Kinematic Theory to examine stroke gestures articulated on touchscreens by people with motor impairments. We report empirical results on 278 stroke gestures collected from 7 participants with spinal cord injury and cerebral palsy, for which we show that the Kinematic Theory can successfully model their strokes and reflect their motor skills entailed by gesture articulation. To encourage and support future work on stroke gesture UIs for users with motor impairments, we show that computer-generated gestures can be successfully synthesized with the same geometric and kinematic characteristics of the gestures actually produced by people with motor impairments.

Author Keywords
Touch input; stroke gestures; motor impairments; spinal cord injury; gesture synthesis; gesture analysis.

ACM Classification Keywords
H.5.2. [Information Interfaces and Presentation (e.g., HCI)] User Interfaces: *Input devices and strategies*; K.4.2. [Computers and Society] Social Issues: *Assistive technologies for persons with disabilities*.

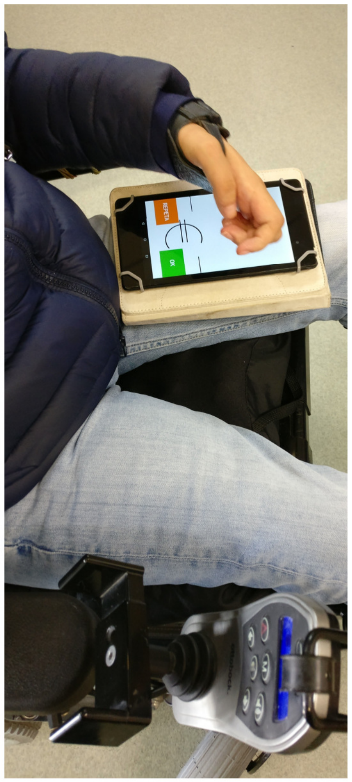

Figure 1: A person with motor impairments (spinal cord injury at the 5th cervical vertebra) drawing the "euro" symbol on a tablet.

Introduction

Stroke gesture recognition is widespread on mobile devices, enabling users to control apps with directional flicks, swipes, and handwritten symbols [18,19]. However, gesture input requires fine coordination of many arm muscles to form a stable hand pose, touch the screen, and control the stability of the wrist, tasks that people with motor impairments find challenging. Motor impairments that affect the upper limbs, such as spinal cord injury, cerebral palsy, muscular dystrophy, Parkinson's disease, arthritis, etc., impede formation of an effective hand pose to touch the screen precisely and confidently (see Figure 1), and are accompanied by poor coordination, fatigue, tremor, and/or numbness.

Prior work has proposed many assistive techniques to improve mouse-based interaction [5], stylus-based text entry [21], and touch input [13] for users with motor impairments, and introduced new input devices [2]. At the same time, researchers have provided valuable insights on the interaction challenges experienced by people with motor impairments [1,12,14], including the accessibility of mainstream wearable technologies [10], and reported comparative evaluations [3]. In this work, we are interested in stroke gestures. In particular, we examine the "quality" of gestures articulated by users with motor impairments from the perspective of the performance criteria of the Kinematic Theory, a highly-effective theory and tool that has been used to model and analyze human movement of many kinds [15,16], including gestures [6-9]. Our results suggest that stroke gestures can be a viable input modality for users with motor impairments. We also show that automatic "gesture synthesis" [6] can be successfully employed to generate samples for training gesture recognizers, removing thus the need for involving users with motor impairments in time-consuming data collection experiments.

The contributions of this work are two-fold:

1. We conduct the first analysis of the performance of people with motor impairments with stroke gesture input by using the criteria of the Kinematic Theory, such as the Signal-to-Noise ratio [16]. Our findings show that stroke gestures produced by users with motor impairments can be effectively modeled in terms of the concepts of the Kinematic Theory as outcomes of many coupled subsystems, for which the velocity profiles are described with sigma lognormal functions [15].
2. We present the first empirical results on gesture synthesis for people with motor impairments by following a recently-introduced approach to generate large datasets for prototyping gesture UIs [6,7]. To prove the feasibility of this approach for users with motor impairments, we compare original and synthesized gestures using state-of-the-art measures of gesture articulation [19].

Experiment

We collected stroke gestures from 7 participants (mean age 38.7 years, SD=8.1) with various motor impairments. Six participants had spinal cord injury (SCI) located at vertebrae C5, C6, or C7 characterized by one or both arms affected by paralysis in various degrees, e.g., a person with traumatic injury at the 5th cervical vertebra (C5) can still perform gross arm movements, but has no control of their wrist or fingers; see Table 1 for details regarding our participants. The experiment consisted in repeated articulations of stroke gestures on a multi-touch tablet device (Asus Google Nexus 7 with a 7.0-inch screen diagonal, display

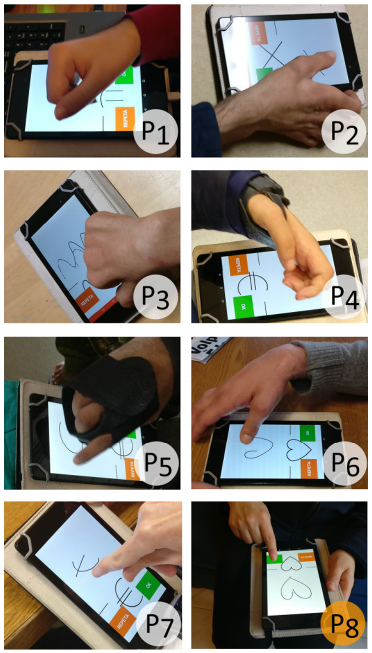

Figure 2: Snapshots of the participants with motor impairments (P_1 to P_7) performing stroke gestures on a tablet. The images show a variety of finger and hand poses, in some cases only possible by wearing hand straps, which reveal various coping strategies adopted by people with motor impairments to use touch input. *Note:* P_8 is a participant without any known motor impairments, used as a control condition; see the text.

No.	Age (yrs.)	Gender	Condition	Gesture articulation details and coping strategy
P_1	37.6	male	Spinal cord injury (C6)	Employs the Swype stroke gesture keyboard frequently for text input on mobile devices. Uses the knuckle of the little finger to enter stroke gestures.
P_2	37.3	male	Spinal cord injury (C6)	Uses the thumb to produce gestures, while the other fingers are fixed to the edges of the device. Because of this strategy, P_2 finds difficult to touch targets in the middle of the screen.
P_3	53.4	male	Spinal cord injury (C7)	Uses the knuckle of the middle finger. Because the hand occludes a large part of the screen during input, P_3 has problems seeing the result, which impacts negatively his accuracy.
P_4	34.7	male	Spinal cord injury (C5)	Has no control over the wrist and, thus, generated many unintended touches. Uses the knuckle of the little finger to enter stroke gestures and a hand strap for support.
P_5	28.5	male	Spinal cord injury (C6)	Because the impairment was acquired relatively recently (2017), P_5 hasn't devised yet an effective strategy to use touch input. During the experiment, P_5 employed the index finger or the knuckle of the little finger. Uses a hand strap for support.
P_6	44.9	male	Spinal cord injury (C6)	Employs the thumb and keeps the other fingers on the physical edges of the device to prevent multiple touches. Can also use the index finger. P_6 is a paralympic tennis table participant and champion.
P_7	34.7	male	Cerebral palsy	Could not finalize the experiment and had to withdraw because of difficulties in producing the symbols. P_7 produced just a few gestures (17.8% completion rate) with the index finger.

Table 1: Demographic details about our participants with motor impairments.

resolution of 1200 × 1920 pixels, and 323 ppi density). An example of the gesture to perform was shown at the bottom of the screen; see Figure 2 for snapshots captured during the experiment. The gesture types that we considered included five symbols: letter "X", the Greek letter "pi", the "euro" symbol, the "heart" shape, and the "energy" symbol (see Figure 5 on the last page for visual illustrations), which we chose for their diversity in terms of the number of strokes (1, 2, and 3), stroke types (straight lines and curves), and geometric complexity[1] (2, 3, 5, 6, and 7, respectively, in the order presented above). Participants were asked to repeat each gesture type for 9 times, with a total expected number of executions of 7×5×9=315 across all participants. In total, we collected 278 gestures, corresponding to a task completion rate of 88.3%.

[1] Evaluated using Ioskoski's measure of shape complexity [4].

Stroke Gesture Analysis

According to the Kinematic Theory, a complex movement, such as handwriting, a signature, or a stroke gesture, is composed of a series of primitives that form the "action plan" of the user implemented by their neuromuscular network to produce the movement [15]. Primitives are described by sigma lognormal velocity profiles that overlap in time to model the profile of the whole movement. We refer the reader to Plamondon et al. [15,16] for mathematical details of the sigma lognormal model and to Leiva et al. [6-9] for instantiations of this model to stroke gesture input.

From our dataset of 278 samples, a number of 273 gestures (98.2%) were successfully modeled with lognormals using the approach of Leiva et al. [6]. We assessed the "quality" of those gestures with the following standard motor performance criteria of the Kinematic Theory [16]:

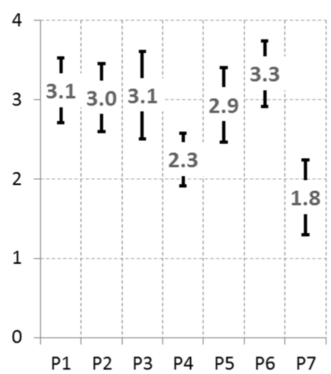

Figure 3: Average SNR/nbLog ratio (error bars show 95% CIs) for the stroke gestures produced by our participants with motor impairments. *Note:* According to the Kinematic Theory, the ratio between the SNR of a human movement and the number of lognormals needed to reconstruct that movement (nbLog) is a strong indicator of the user's motor control ability. According to the expected values for this indicator (i.e., between 2 and 10; see Plamondon et al. [16]), these results show suboptimal motor abilities for our participants.

1. The **signal-to-noise ratio (SNR)** computed between the original and reconstructed velocity profiles accounts for the reconstruction quality of a gesture. Higher values denote better performance.
2. The **number of lognormals (nbLog)** is a descriptor of the user's gesture articulation ability. Lower values represent better user performance.
3. The **SNR/nbLog ratio** is a global indicator of the user's motor skills reflected by the "lognormality principle" [15], i.e., users who are in perfect control of their movements produce a minimum number of lognormals during a specific movement. Higher values denote better user performance.

The average number of lognormals was 8.1 (SD=4.4) and the average SNR was 19.2 dB (SD=4.7 dB). For stroke gestures produced by people without motor impairments, the literature has reported nbLog values between 1 and 10 and SNR ratios between 15 and 30 dB [6,11,16]. To better understand these results for our specific gesture types, we also asked one person without motor impairments (35.3 years) to produce the gestures with results showing better motor abilities (nbLog=6.0, SD=1.4 and SNR=22.9 dB, SD=3.4). Typical values for the SNR/nbLog ratio fall between 2 and 10; see Plamondon et al. [16]. Usually, children (in the process of acquiring motor skills) and elderly people (diminished motor skills) show SNR/nbLog values on the lower end of the typical range [16]. The average ratio for our participants was 2.8 (SD=0.6), see Figure 3, while the control participant achieved 4.0 (SD=1.1).

These results show that motor impairment is reflected in a large number of subsystems that are badly timed. The coupling must appear as a proportionality relationship in the cumulative time delays of these subsystems. Thus, for stroke gestures, the vector addition process [15] is affected and people with motor impairments need to adopt coping strategies, which reflect in a tendency to compensate their suboptimal subsystem timing (i.e., low SNR) with a large number of lognormals (high nbLog) to reach their goal. Our results also show that users with motor impairments can produce gestures effectively according to the motor performance criteria set by the Kinematic Theory, although they do so with more effort and with various coping strategies (see Figure 2 and Table 1). Thus, stroke gestures can be a viable input modality for users with motor impairments, just like other forms of input [17], although utilized at suboptimal performance.

Stroke Gesture Synthesis

The results so far show that the Kinematic Theory can be successfully employed to model stroke gestures produced by people with motor impairments as well as to evaluate their gesture articulation skills. In the following, we look at a very recent application of the theory for the generation of large datasets, a process known as "gesture synthesis" [6]. Prior work showed that computer-generated gestures that mimick users' gesture articulation characteristics with high fidelity [8] can be used to prototype gesture recognition [6,7] or to predict users' performance with gesture input [9]. Especially for people with motor impairments, collecting large training data is impractical. Instead, gesture synthesis techniques, such as G3 [6] or its specific instantiations [7,9], can generate a large number of gesture variations from just one example. In this section, we are interested in whether the synthesis approach works for stroke gestures produced by people with motor impairments. To this end, we used the G3 API [6] to generate synthetic versions of our gesture

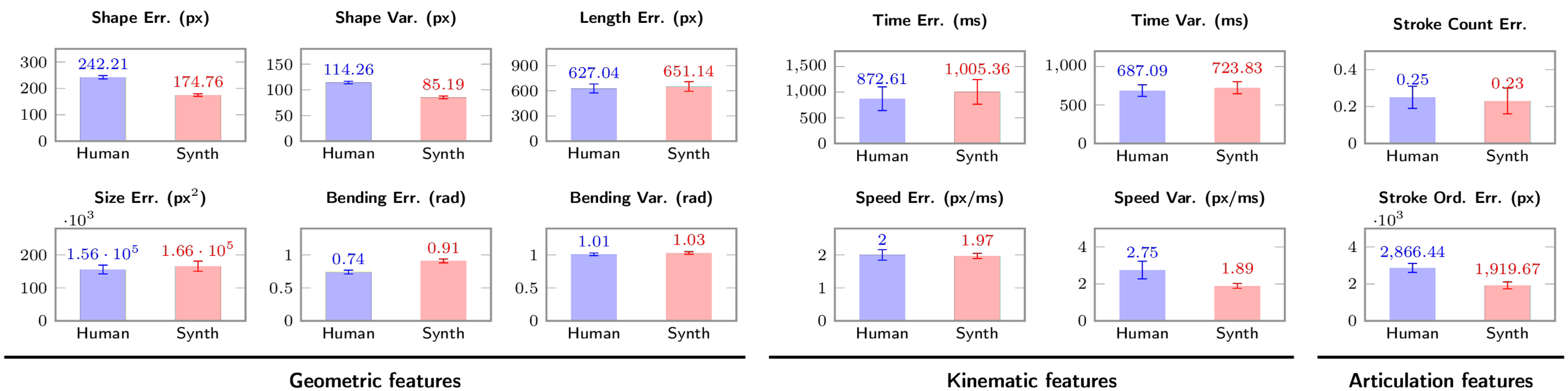

Figure 4: Gesture relative accuracy measures [19] computed for original and synthetic gestures; also see Table 2 for statistical analysis. Error bars show 95% CIs.

Gesture measure	t-test (*df*=4)	*p*-value
Length Error	-0.444	.680
Shape Error	2.077	.106
Size Error	-1.126	.323
Shape Variability	1.477	.214
Bending Error	-2.776	.050
Bending Variability	-0.591	.586
Time Error	1.824	.142
Time Variability	-0.764	.488
Velocity Error	0.169	.874
Velocity Variability	-2.526	.065
Stroke Error	0.579	.594
Stroke Order Error	1.281	.270

Table 2: Statistical analysis results for original vs. synthetic gestures. *Note*: all *p*-values are above the .05 level of statistical significance.

types. In total, we generated N=273 gestures, one for each original. To understand how well the synthetic strokes reflect the articulation characteristics of people with motor impairments, we compared them with the originals using the set of 12 gesture relative accuracy measures of Vatavu et al. [19]. This set of measures evaluates the deviation of a stroke gesture from a representative template, in our case the original gesture, in terms of its geometry, kinematics, and articulation pattern. For instance, Shape Error (Figure 4, top left) reports the Euclidean distance between a candidate gesture and the template; see Vatavu et al. [19,20] for definitions and examples. Statistical tests showed no significant differences between originals and synthetic gestures (see Table 2), which suggest that gesture data can be successfully generated for people with motor impairments to foster development of gesture technology (such as gesture recognition [6-8] or gesture set design [9]) for this user group, developments that we recommend for future work.

Conclusion

We examined in this work stroke gestures produced by people with motor impairments on touchscreens by using the concepts and tools of the Kinematic Theory. Our empirical results recommend stroke gestures to be further explored by the community as a viable input modality for users with motor impairments as their articulations meet the motor performance criteria set by the Kinematic Theory. Towards this goal, we showed that powerful state-of-the-art techniques, such as gesture synthesis, can be successfully employed to readily generate large datasets, which opens new opportunities for prototyping gesture UIs for users with motor impairments. Our gesture dataset is available from the web address http://www.eed.usv.ro/~vatavu, free to download and use for research purposes.

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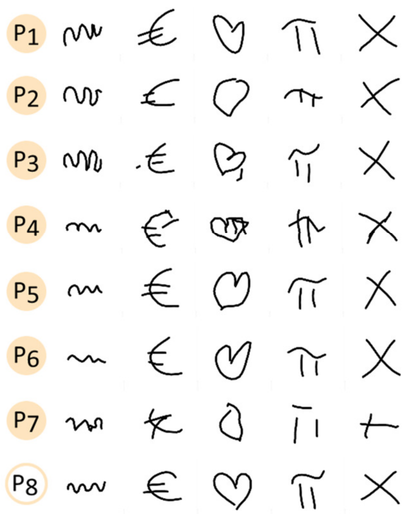

Figure 5: A selection of the stroke gestures produced by our participants: the "energy" symbol, the "euro" symbol, the "heart" shape, Greek letter "pi," and letter "X." *Note:* P_8 is a participant without any known motor impairments, used as a control condition; see the text.

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