The Effects of Prosthetic Tactile Feedback on Persons Who Stutter

by

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ABSTRACT

Vibrotactile speech feedback has been documented to enhance fluency in adults who stutter. Based on these data, researchers at the University of Mississippi have developed a prosthetic device that captures the speech signal of the speaker, converts this signal into tactile stimulation, and administers vibratory speech feedback to the speaker through a handheld stimulator. This patented device, as tested with a handheld tactile stimulator, has been documented as producing significant fluency enhancement comparable to that of other auditory speech feedback prosthetic devices. The purpose of this present study is to collect data measuring the effects of tactile speech feedback on overt stuttering frequency as a function of different bodily locations as a means to increase its wearability and improve user experience during activities of daily living. Twelve adults who stutter (AWS) ranging from 18 to 43 years of age were prompted to read various ~300 syllable passages under four different conditions: a no stimulation control speaking condition and experimental speaking conditions that tactilely stimulated the hand, dominant wrist, and dominant foot. Results suggest a significant main effect of tactile speech feedback on fluency enhancement, with Bonferroni post-hoc comparisons revealing that the foot condition provided significantly better fluency enhancement than other speaking conditions. Prosthetic implementation and future applications of the device are discussed.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

AWS	Adults Who Stutter
SSS	Second Speech Signal

INTRODUCTION

Stuttering is typically defined as a speech disorder characterized by part-word and whole-word repetitions, prolongations, and inaudible postural fixations; these overt stuttering behaviors are often accompanied by covert behaviors that may include tension, novel gestures paired with speech production, word substitution, and word avoidance. Signs and symptoms of stuttering generally appear between two to four years of age, although between 50% and 80% of children demonstrating stuttering-like disfluencies will spontaneously recover. For the minority of children who do not spontaneously recover from producing stuttering-like disfluencies, stuttering will persist into adulthood, affecting approximately 1% of the global population— or more than 70 million people worldwide [Bloostein & Ratner, 2008].

Currently, mainstream stuttering treatments rely heavily on behavioral speech targets. The two most common behavioral therapy philosophies are fluency shaping— which has an end goal of fluent speech— and stuttering modification— which deals with the desensitization and modification of overt stuttering behaviors. Clinically, these two approaches are often combined, with therapy sessions consisting of stuttering desensitization, personal acceptance, and instruction on speech-motor techniques such as the prolongations of sound, slowed rates of speech, or controlled breathing [Bloodstein & Ratner, 2008; Prins & Ingham, 2009]. Although often temporarily effective, these techniques have been reported to sound unnatural and require a significant amount of cognitive effort, which commonly result in therapeutic relapse and high therapeutic dropout rates in clients who stutter [Dayalu & Kalinowski, 2002; Prins & Ingham, 2009]. Consequently, the ineffective treatment of stuttering can have a severe effect on social and emotional functioning, quality of life, and the mental health status of adults who stutter (AWS), emphasizing the importance of finding new treatments to improve the quality of life [Craig, Blumgart, & Tran, 2009]. Therefore, a new scientific paradigm in the science and treatment of stuttering may allow researchers to explore new, and possibly more effective, stuttering treatments—thereby improving the quality of life for the stuttering population.

Recent data suggests that persistent stuttering may not be as simple as a stand-alone speech disorder, but rather a much larger genetic and neurological condition that manifests itself within multiple expressive modalities, only one of which is speech [Snyder, 2006]. This theory accounts for the stuttering-like fluency disruptions observed in various modalities of expressive communication, including speech, musical expression, handwriting, and sign language [Snyder, 2006]. Data also reveal that persistent stuttering has a strong genetic substrate. Mutations found to be causal to stuttering have been discovered on a number of chromosomes in AWS; specifically, Raza et al. (2015) synthesizes this information with findings that indicate that all of the causal genetic variants documented thus far are a part of the same intracellular trafficking process within adaptor-related protein complex 4, epsilon 1 subunit (AP4E1) [Raza et al., 2013; Raza et al., 2015; Riaz et al., 2005; Kang et al., 2010]. Accordingly, these genetic data support the notion that genetically induced persistent stuttering is best considered as a medical condition associated with errors in intracellular trafficking [Raza et al., 2015].

Overt stuttering behaviors are also associated with specific functional neurological processing abnormalities, such as increased neuromotor preparation in the production of fluent words in comparison to stuttered words; specifically, these anomalies were discovered within the basal ganglia-thalami-cortical (BGTC) loop, the most important cortical pathway for motor preparation for speech [Vanhoutte et al., 2015; Vanhoutte et al., 2016]. This suggests that persistent stuttering has a genetic genesis representing errors in intracellular trafficking, which leads to hallmark functional neurological processing abnormalities associated with stuttered and fluent speech production [Snyder, Waddell, & Blanchet, 2016a]. In what is known as the compensation hypothesis, it is proposed that in the fluent initiation of linguistic gestures, select left hemispheric neural activation abnormalities— coupled with right hemispheric homologous activity— likely represent natural compensatory strategies relative to addressing breakdowns at the more central level [Vanhoutte et al., 2015]. This genetic hypothesis has also been extended to account for many overt stuttering behaviors, including prolongations and repetitions. Accordingly, stuttering behaviors may not represent the disorder of stuttering, but rather have been proposed to serve as gestural priming as a means to address the disorder by initiating fluent speech [Snyder, Waddell, & Blanchet, 2016]. As these data are influencing a paradigm shift within the science and treatment of stuttering, researchers are looking at treatments that directly address the neural substrate of stuttering, instead of modifying the compensatory behaviors that represent overt stuttering behaviors themselves.

Second Speech Signal

A second speech signal (SSS) is the simultaneous feedback of a gesturally similar speech signal relative to the primary spoken speech signal; it provides a strong link between the perception and production of target speech gestures, which is hypothesized to be the neurological rationale for subsequent fluency enhancement in those who stutter [Kalinowski et al., 2000; Snyder & Jones, 2017]. Perhaps the most effective and common use of a SSS is the choral speech phenomenon—when a second speaker produces similar speech in choral unison with the AWS [Kalinowski et al., 2000]. Virtually immediately, the speech of the AWS exhibits fluency comparable to that of a normal speaker, and covert secondary behaviors are minimized [Kalinowski, & Saltuklaroglu, 2003]. However, past researchers viewed choral speech merely as a trick to demonstrate the capacity for fluency; as a result, it was not popular to implement clinically [Kalinowski, & Saltuklaroglu, 2003]. Alternately, there is extensive literature on other prosthetic uses of speech feedback (e.g. masking, delayed auditory feedback, frequency altered feedback) to treat stuttering, but it has been primarily executed in the auditory sensory modality until the discovery of visual choral speech [Kalinowski, Armson, Roland-Mieszkowski, Smart, & Gracco, 1993; Kalinowski, Stuart, Rastatter, Snyder & Dayalu, 2000]. Accordingly, past researchers attributed fluency enhancement resulting from prosthetic speech feedback as a byproduct of correcting auditory and/or speech-related temporal processing errors, which was a common perspective that led to previous popular research paradigms relative to the perceived etiology of stuttering [Cherry & Sayers, 1956; Webster & Lubker, 1968].

However, researchers expanded beyond the auditory modality when they documented comparable fluency enhancement via the visual representation of a speech gesture (i.e. visual choral speech) [Kalinowski et al., 2000]. Ten adults who stutter recited memorized phrases under two conditions. In the control condition, participants were instructed to recite the memorized phrase while focusing on the lips and jaw of a motionless research assistant. In the visual choral speech condition, participants were instructed to recite their passages aloud while focusing on the lips and jaw of the research assistant who silently mouthed the words synchronously. Participants in the visual choral speech condition experienced a reduction in stuttering by approximately 80%— which was the first documentation of implementing visual choral speech without an accompanying auditory signal [Kalinowski et al., 2000]. This study contributes to the body of stuttering research literature in that the data point not to an error in auditory processing alone, but instead to an error in the processing of speech at a more central level [Snyder et al., 2016; Jones, 2017; Vanhoutte et al., 2016].

Hypothesizing that fluency enhancing speech feedback is truly a multi-modal phenomenon, Snyder [2009a] documented significant fluency enhancement via vibrotactile speech feedback by directing the person who stutters to feel the vibration of the thyroid cartilage while producing speech. Eight AWS documented an approximate reduction in stuttering frequency by 72% [Snyder et al., 2009a]. Research suggests that speech feedback methods in form of visual choral and tactile feedback were effective because they still provided a gesturally similar speech signal, allowing the AWS to connect the perception and production of the target speech gesture [Kalinowski et al., 2000; Snyder et al., 2009a]. Research documents that the use of a SSS can be carried out in multiple sensory modalities to reduce overt stuttering behaviors; therefore, the understanding of its efficacy cannot be attributed to an auditory processing disorder alone, but rather an underlying neurological substrate that encompasses this phenomenon as a whole [Snyder et al., 2016]. Subsequently, a new paradigm for the science and treatment of stuttering is emerging as a result from the intersection of neurological and genetic data, along with the multi-sensory nature of fluency enhancement via a SSS.

Mirror Neurons and Action Understanding

To explain the phenomenon of enhanced fluency as a function of a SSS, researchers have pointed to mirror neurons as the underlying mechanism [Kalinowski & Saltuklaroglu, 2003; Snyder et al., 2016; Snyder & Jones, 2017]. Mirror neurons were first introduced in the observation of primates, with the term being coined after investigators observed that when a primate perceives an action (i.e. picking up a cup), the same neurons are triggered as though the observer is completing the action. These neurons happen to be activated in area F5 of the monkey brain, which is widely accepted to be the monkey homolog of Broca's area in the human brain, responsible for motor speech [Rizzolati & Arbib, 1998]. Since then, researchers have observed an equivalent system in the human brain that is activated when people imitate actions [Rizzolati & Arbib, 1998; Corballis, 2010]. This observation links mirror neurons with the perception and production of motor speech behaviors, and is suggested as a necessary component in the evolution of communication that links the sender and receiver [Corballis, 2010; Snyder & Jones, 2017; Kalinowski & Saltuklaroglu, 2003].

One striking characteristic in the observation of mirror neurons is that they do not necessarily fire in accordance to individual movements (e.g. picking up with the right hand or picking up with the left) but instead to the intent of the action itself (grasping) [Rizzolati & Arbib, 1998]. In other words, they mirror the goals instead of the specific action. This is also a key characteristic of action understanding— the neural process of understanding the goal of others' actions without having to perform the actions themselves [Corballis, 2010; Jones, 2017]. Mirror neurons allow for the observer to map the perception of an action onto his or her motor representation, achieving instant understanding [Snyder & Jones, 2017]. If action understanding is achieved through mirror neurons, it has several implications as a neurological framework for fluency enhancement in AWS. First, the closer the stimulus is to the desired action, the more automatic action understanding via mirror neurons will be; in other words, gestural primes most similar to the target gesture itself will likely have greater fluency enhancement [Jones, 2017]. To test this implication, Jones [2017] documented that when using gestural primes more similar to speech (i.e. lightly striking the table, a self-generated tongue click, and a silent opening mouth gesture), fluency was most efficaciously enhanced in the condition most similar to speech production.

It is also hypothesized that when an AWS perceives a gesturally similar SSS in the auditory, visual, or tactile modalities, action understanding is achieved via mirror neuron networks, thereby bypassing the suggested areas of functional neural processing abnormalities associated with stuttered speech, and instead producing more fluent speech [Snyder et al., 2016a; Snyder & Jones, 2017]. Accordingly, research suggests that stuttered speaking behaviors may actually represent a natural compensatory strategy to the underlying stuttering pathology by using gesturally similar behavioral primes (i.e. repetitions and prolongations) as a means to endogenously activate the mirror neurons and produce fluent speech, in accordance to the compensation hypothesis [Snyder & Jones, 2017]. With data suggesting mirror neurons' strong link to language and its activation without training, it has to operate at a more central level in order to bypass the more peripheral neurological breakdown associated with stuttering within the BTGC loop [Snyder et al., 2016; Snyder & Jones, 2017]. Through utilizing action understanding via the mirror neuron system that is already integral within human language, we can use a SSS to directly provide AWS with the fluent framework for speech without any of the peripheral processing that is involved in behavioral therapy techniques [Snyder et al., 2016; Snyder & Jones, 2017].

Current Application of Research

Although the use of auditory, visual, and tactile feedback has been documented to successfully enhance fluency in AWS [Kalinowski et al., 1993; Kalinowski et al., 2000;Snyder et al., 2009], auditory and visual SSS could serve as significant distractions to the speaker and to the interpersonal communication process, thereby impeding the naturalness and efficiency of spoken communication across various contexts and activities of daily living [Bothe, Finn, & Bramlett, 2007; Pollard, Ellis, Finan, & Ramig, 2009]. While externally generated choral speech is the most marked and effective fluency enhancement method, it simply cannot be successfully implemented in real-world settings [Bothe et al., 2007]. However, an internally generated SSS, such as delayed auditory feedback and frequency altered feedback, can approximate fluency enhancement associated with choral speech [Kalinowski & Saltuklaroglu, 2003; Waddell et al., 2012]. Accordingly, fluency enhancing altered auditory feedback has been prosthetically exploited to reduce overt stuttering frequency in those who stutter [Janus Development Group, 2005].

The most prominent prosthetic application of altered auditory feedback in mainstream stuttering treatment has been through the SpeechEasy, an in-the-ear device that utilizes both delayed auditory feedback and frequency altered feedback to enhance fluent speech [Janus Development Group, 2005]. While data documents a 56% reduction in disfluencies when reading in the treatment phase, qualitative reports from this same study noted that participants are most unsatisfied with irritating background noise, not being able to understand one's self or others, and its lack of usefulness in noisy or crowded settings as well as when under stress [Pollard et al., 2009].

Tactile feedback has the potential to bypass the auditory and visual impediments relative to spoken communication, thereby better incorporating itself into the daily activities of living. Consequently, prosthetic tactile feedback is now being explored as a viable form of stuttering management in the lives of AWS. At the University of Mississippi, researchers have applied these findings to develop a prosthetic device that captures the vocalization of the speaker through the use of an accelerometer embedded within a transducer collar and administers vibratory speech feedback through a tactile stimulator [Waddell, Goggans, & Snyder, 2012]. As the accelerometer only captures vocal vibrations via the thyroid cartilage, it is not susceptible to excess background noise, thereby resolving signal to noise issues that are common to auditory SSS devices. Accordingly, the discrete tactile stimulator allows for the user to access stable speech feedback across multiple contexts and difficult environmental settings.

This patented device has been tested with the tactile stimulator placed in the hand, and the results reveal a decrease in overt stuttering moments by approximately 80% [Waddell, Goggans, & Snyder, 2012]. However, the goal of this technology is the seamless integration into daily life both cognitively and physically. In terms of practical daily use, AWS will be best served if their hands are not tethered to the tactile feedback stimulator. In view of a successful prosthetic implementation of this technology, the purpose of this present study is to test the effectiveness of prosthetic tactile feedback on overt stuttering frequency as a function of stimulating different locations of the body in order to assess and optimize future applications of the technology.

METHODS

Participants

Twelve adults who stutter (nine men, three women), ranging from 18 to 43 years of age (median age = 25, mean age = 27.25, SD = 8.50802), participated in this study. All participants reported no other diagnosed speech, language, hearing, or attention disorders, and have obtained at least a high school diploma. None of the participants were currently enrolled in treatment, although they all reported a history of speech therapy. The Institutional Review Board at The University of Mississippi approved this study, and each participant provided written consent.

Instrumentation

The prosthetic device was developed at the University of Mississippi and patented in 2016 (US Patent: 9263043 B2). It consists of four main components: the transducer collar, accelerometer, processor, and tactile stimulator. The transducer collar is worn around the neck on either side of the thyroid notch; its purpose is to capture the vocalizations of the speaker. The accelerometer records the vibrations and sends it to the processor, which then converts the information into tactile feedback, administered through a small disk that is the tactile stimulator. [Snyder, Waddell, & Goggans, 2016b; Waddell et al, 2012].

Study Design

This study modified the design used in a previous peer reviewed study [Waddell et al., 2012]. Participants were instructed to read several junior-high level passages averaging ~300 syllables under four assigned conditions: (a) no device, (b) collar worn, handheld tactile stimulator (c) collar worn, tactile stimulator taped to wrist, and (d) collar worn, tactile stimulator taped to foot. The tactile stimulator was taped to the wrist and foot using medical tape. The passages were taken from junior high textbooks, all of which have been used in previous experiments [Kalinowski et al., 2000; Snyder et al., 2009a; Snyder et al., 2009b; Snyder et al., 2016a]. Every participant read the control condition first in order to prevent carry-over of fluency from the device. In order to control all other order effects for the experimental speaking conditions, a Latin square was used to balance the passages and speaking conditions. Participants were given a demonstration and practice trial with the device before reading the passages. Successful utilization of tactile feedback requires the users to attend to the tactile stimulation during speech production [Snyder et al., 2009b]. In light of this finding, participants were instructed to attend to the feedback and read aloud as normally as possible, without using any speech controls.

Data Collection and Analysis

Participants were video and audio recorded using a Canon EOS Rebel T3i. For the purposes of this study, stuttered syllables were defined as part-word and whole-word repetitions, prolongations, and inaudible postural fixations [Bloodstein & Ratner, 2008]. The principle investigator counted and analyzed the data. A trained research assistant was used to perform inter-judge reliability testing.

RESULTS

As shown in Figure 1, the use of vibrotactile prosthetic speech feedback was found to reduce stuttering frequency by approximately 36%, 12%, and 40% relative to hand, wrist, and foot placement. The raw data (as shown in figures 1 and 2), revealed a large variance in stuttering severity per participant; as a result, these raw data were transformed via a natural log (ln) data transformation as a means to provide a more normalized and symmetrical distribution of these data [Jones, Onslow, Packman, & Gebski, 2006]. Using these transformed data, a RM-ANOVA revealed a main effect of vibrotactile prosthetic speech feedback [$F(3,33) = 7.406$, Greenhouse-Geisser $p = 0.004$, $\eta^2 = 0.402$]. Figure 3 shows the average number of stuttered syllables per speaking condition across all participants, with the foot and hand conditions having notably less stuttered syllables. Bonferroni post-hoc testing revealed that overt stuttering frequency, as a function of the control versus foot stimulation ($p = 0.010$), and wrist stimulation versus foot stimulation ($p = 0.043$), were significantly different.

Intrajudge and interjudge reliability compared the analysis of 10% of the speech samples, chosen at random, with the original analysis of the data. Relative to stuttering frequency, an intrajudge syllable by syllable agreement was > 0.92, as indexed by Cohen's kappa [Cohen, 1969]. A second trained research assistant and the principal investigator both recalculated this 10% of the speech sample, chosen at random and found the stuttering frequency interjudge syllable-by-syllable agreement was > 0.88, as indexed by

Cohen's kappa [Cohen, 1969]. Kappa values exceeding 0.75 suggest an excellent agreement beyond chance [Fleiss, 1981; Costa & Kroll, 2008].

Figure 4 allows for closer observation of the effects of each condition individually. Participant number three showed the most dramatic results with a reduction in stuttering frequency by approximately 89%, 33%, and 67% relative to hand, wrist, and foot placement. It should also be noted that participant eleven showed no trending results, with the number of stuttered syllables actually increasing during experimental speaking conditions. This participant self reported that auditory speech feedback via a SSS— specifically through the SpeechEasy device— was not effective even after use for a prolonged period of time. Since the participant reported no previous effect to other speech feedback devices, it could serve as exclusion criteria for future studies. Without participant number eleven included in the data, overall stuttering reduction was increased by 47%, 26%, and 47% relative to hand, wrist, and foot placement.

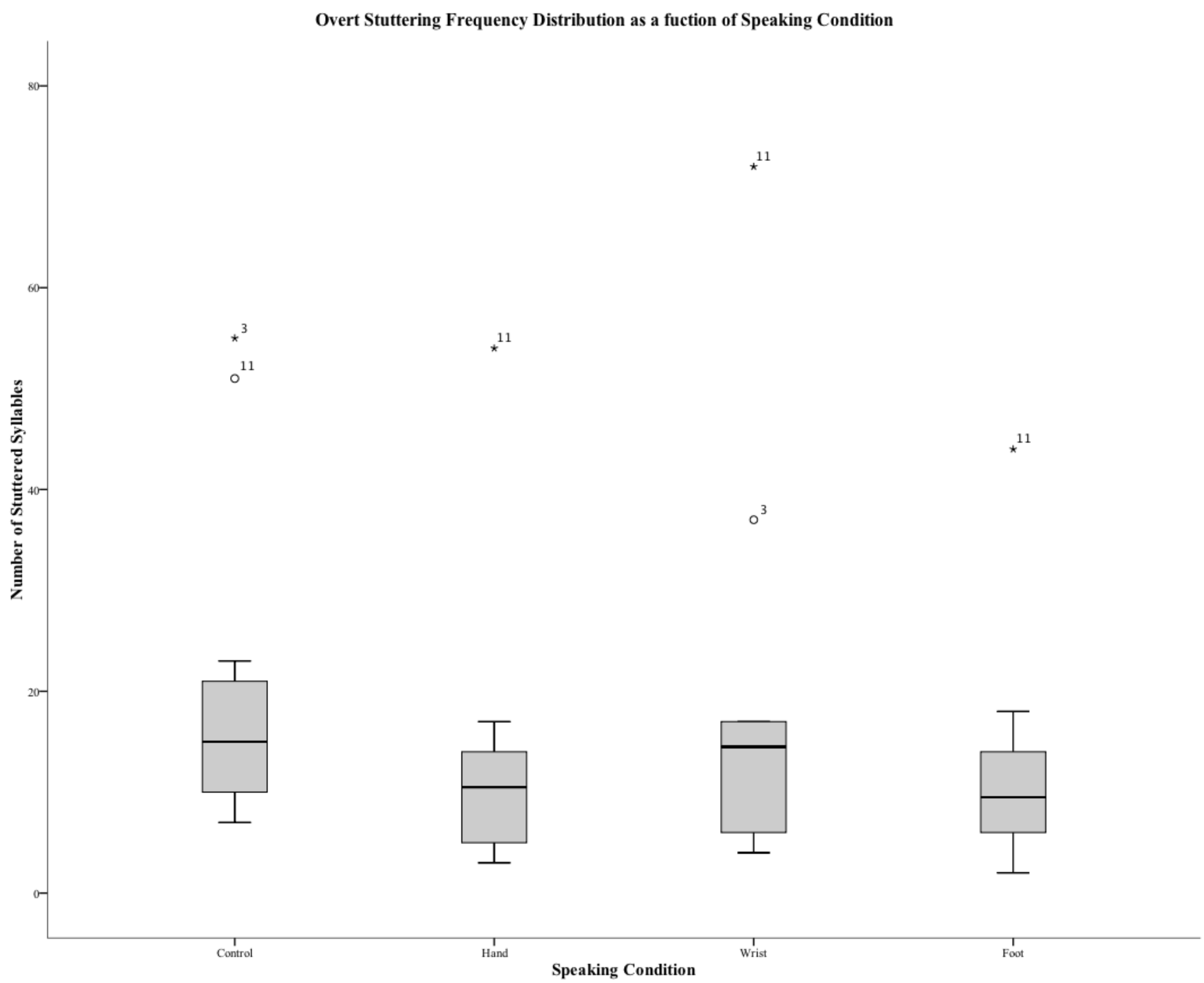

Figure 1. Minimum, maximum, interquartile range, and median values for the control, hand, wrist, and foot speaking conditions

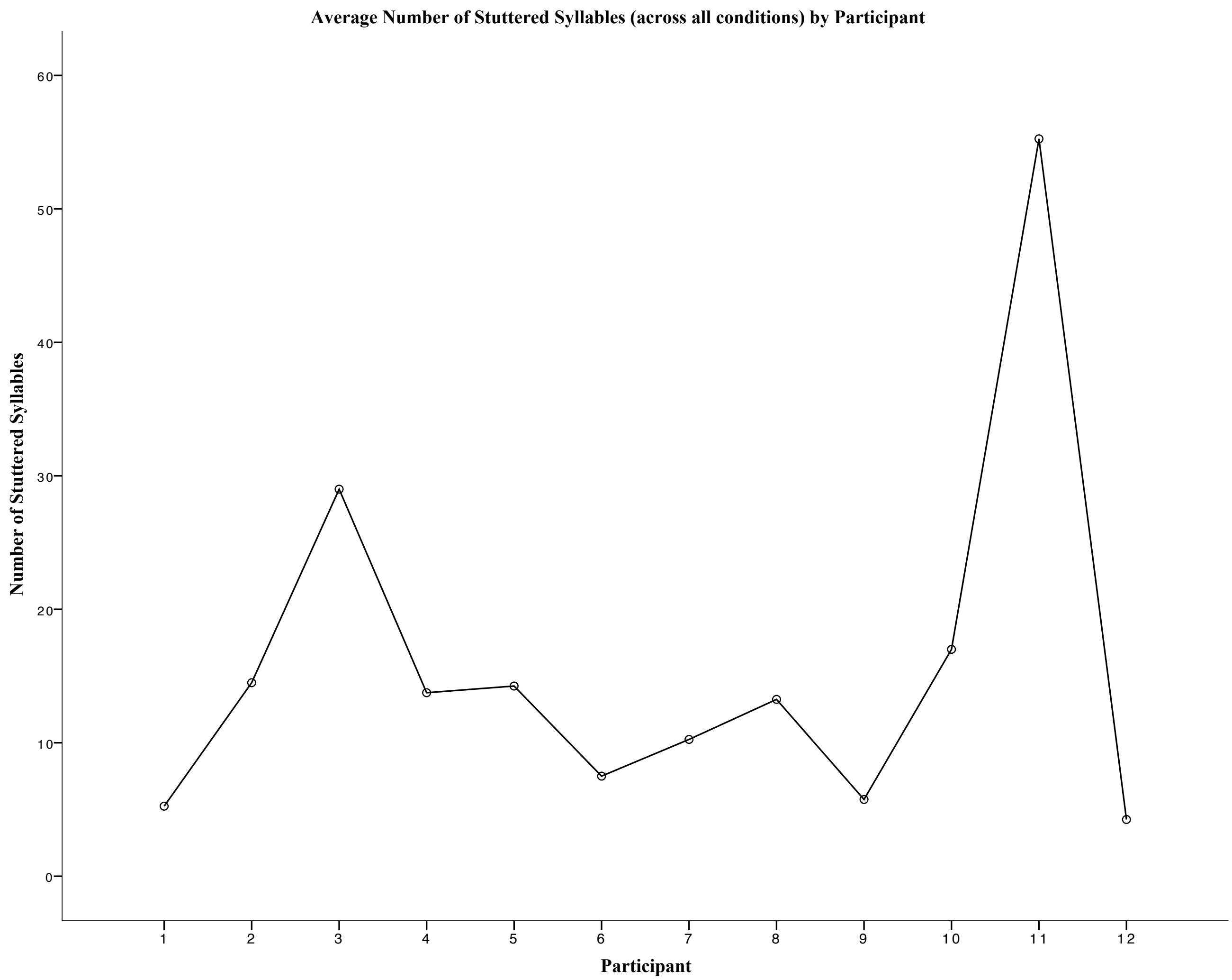

Figure 2. *Raw data of participant by average number of stuttered syllables across all conditions*

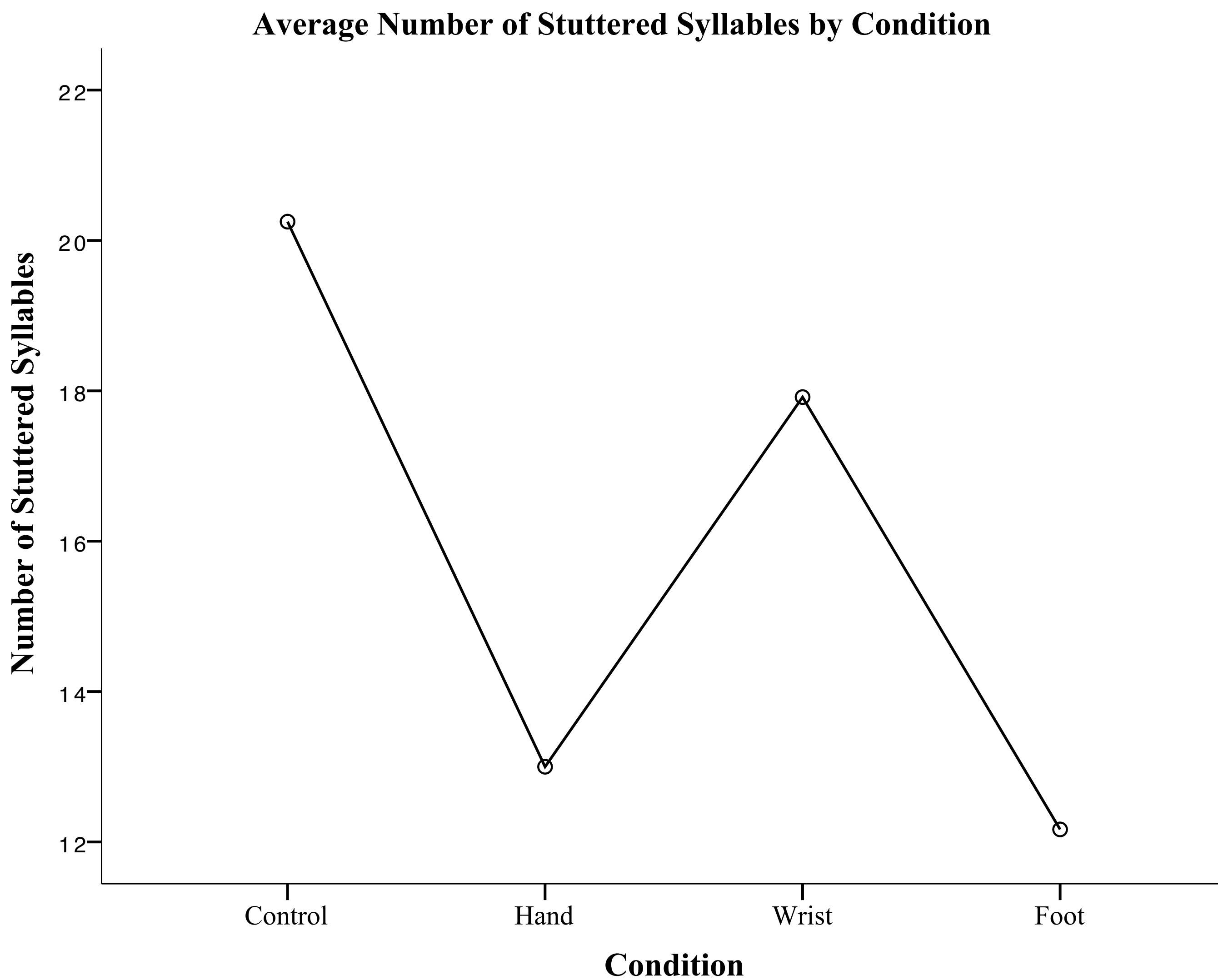

Figure 3. *Raw data of speaking conditions by number of stuttered syllables*

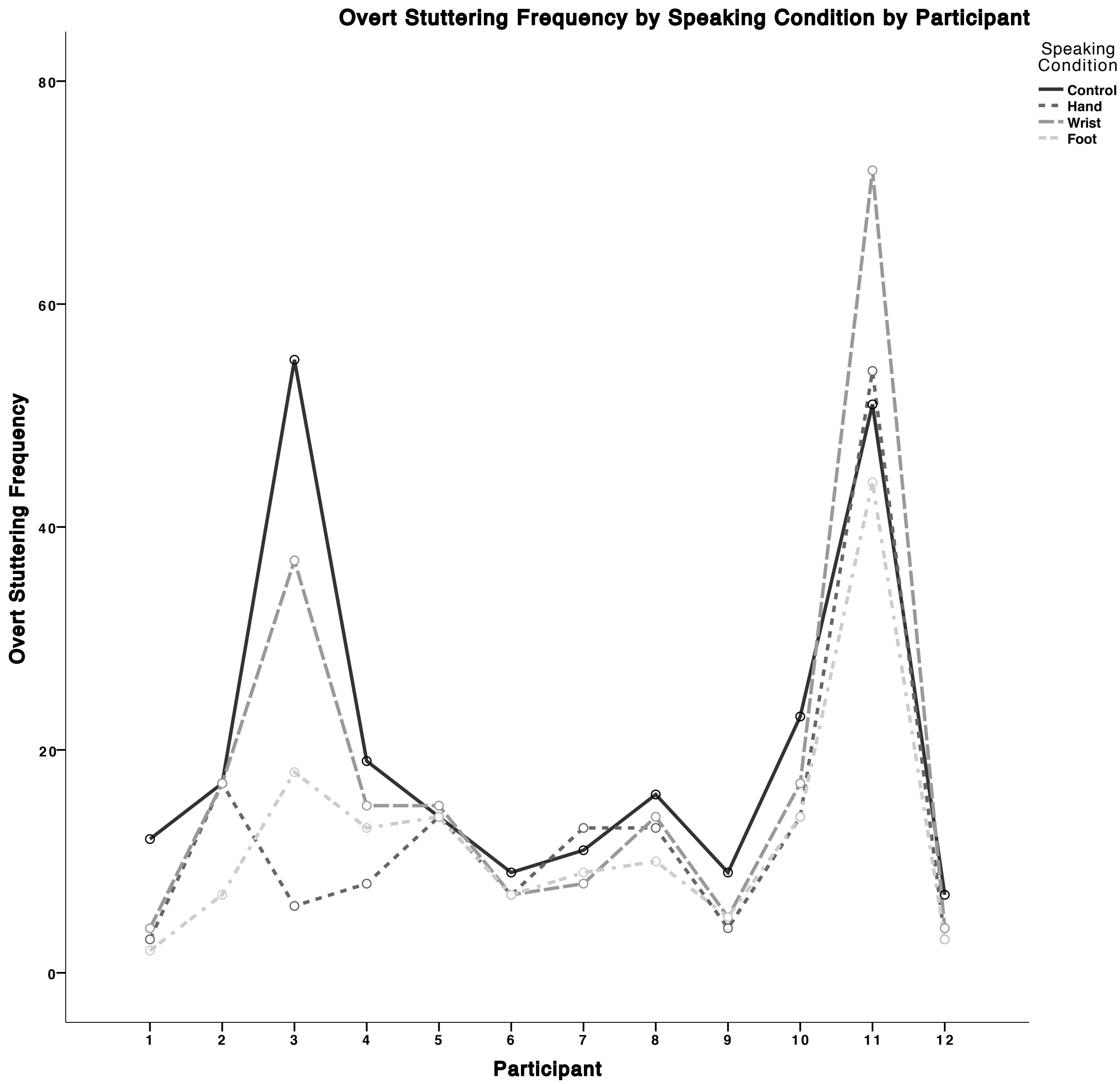

Figure 4. *Number of stuttered syllables per participant, in terms of speaking condition*

DISCUSSION

Post-hoc testing indicates that body location significantly affects fluency enhancement, with the foot being the most efficacious bodily locations, followed by the hand with similar results, and the wrist with very little fluency enhancement. This is perhaps due to greater neural density in these areas compared to the wrist [Nakamura et al., 1998]. This supports a hands-free model for the device.

Accounting for a reduced level of fluency enhancement, relative to previous fluency enhancing SSS prosthetic data, is not readily apparent. Apart from the small sample size, and differential overt stuttering severity of the participant group used in this pilot study, another explanation may be found in a previous study documenting that stuttering participants reported indirect representation of a tactile SSS was less automated than other sensory modalities in the subsequent fluency enhancement [Snyder et al., 2009]. Consequently, it is suggested that as tactile feedback is farther removed from representing actual speech gestures, relative to the auditory or visual sensory modalities, additional time, practice and training may be needed to link feedback perception with speech production in order to increase fluency in AWS. Accordingly, data such as these support the notion that fluency enhancing tactile speech feedback is activated through action understanding via mirror neuron networks, which operate best when the priming gesture is most similar to the gestural target [Snyder et al., 2016a; Jones, 2017]. Although the participants were initially given time to train with the hand-held tactile stimulator, more time and expressed clinical training for each bodily location may result in greater fluency enhancement.

In examining the individual effects of bodily location on fluency enhancement, each participant showed great variance in the baseline number of stuttered syllables and primary and secondary behaviors associated with stuttering. Participant number five and participant eleven both showed no effect, with participant number eleven reporting that previous speech feedback techniques had not been effective. The primary investigator observed that participant eleven's stuttering behaviors were characterize by inaudible postural fixations (i.e. blocks); this is an important observation, as it has been documented that speech feedback devices such as the SpeechEasy— and thus tactile speech feedback devices used to prime the following speech gesture— cannot effectively enhance fluency because no speech signal and thus no speech feedback is being provided [Kalinowski, Saltuklaroglu, Stuart, & Guntupalli, 2007]**.** It may be more effective to have more in-depth analysis of the types of stuttering behaviors that accompany results, as it can aid information that determines which genetic version of persistent stuttering is susceptible to this type of treatment.

Future research may look at the development of shoe inserts as a method of providing the fluency enhancing tactile speech feedback; another implementation may be the development of a ring, worn on the finger, that has the ability to provide prosthetic vibrotactile speech feedback without interfering with the user's manual movements. These possible innovations relative to the prosthetic implementation of tactile speech feedback would also have to be wireless, perhaps by incorporating Bluetooth wireless technology. If results are tied directly to neural density, targeting other neuronally dense areas may be an area of future research, such as the upper arm [Nakamura et al., 1998]. The prosthetic device could then implement its speech feedback through the use of a band worn around the upper arm. We also aim to examine the carry-over affects of long term use of this device and analyze its impact on spontaneous speech as it will be more generalizable to daily life. Although results of bodily location were not comparable to that of other speech feedback signals, measurable improvement in the hand and foot condition indicate that it may still be the best option for integrating fluency enhancing technology into daily life as seamlessly as possible.

Conclusion

These data reveal differential fluency enhancement as a function of the bodily location and vibrotactile prosthetic speech feedback. While effective, fluency enhancement documented in this particular study was not as robust as other auditory SSS prosthetic implementations; these data reveal that the foot condition recorded the most efficacious fluency enhancement. However, a small data set, large inter-participant variability, and promising data suggest that further research is warranted. With data suggesting that hand and foot stimulation sites provide the most efficacious fluency enhancement, developing the device into a bluetooth shoe-insert or a prosthetic stimulator in the fashion of a ring or armband is predicted to provide optimal fluency enhancement with maximum wearability during activities of daily living. This allows AWS to better incorporate this technology into daily life, therefore significantly improving the quality of life for AWS.

Conflicts of Interest

There are no conflicts of interest.

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