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Initial development of a method to quantify ankle force perception in young adults

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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
of Emory University in partial fulfillment
of the requirements of the degree of
Bachelor of Science with Honors

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Abstract

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Background: Force perception is comprised of two primary inputs: sensory feedback and the motor command. Currently, force perception has only been assessed in the upper limb, which has shown a trend of overestimating when trying to reproduce low forces and underestimating when trying to reproduce high forces. Additionally, the ability of persons to reproduce brief non-voluntary wrist force contractions due to muscle stimulation was found to be poor. Little is known about force perception in the lower limb, but force perception is likely important for lower limb behaviors like ankle propulsion when walking.

Objective: The goal of this study is to develop a method to quantify ankle force perception and use this method to distinguish the roles of force-related feedback and the motor command in force perception. Our three objectives include characterizing force matching ability at five force levels in able-bodied adults, evaluating learning effects within session and across days, and examining force matching with the reference force arising from muscle stimulation.

Methods: A force matching paradigm was used with eight young, able-bodied subjects. All eight subjects participated in two days of ankle plantarflexion voluntary force matching at five force targets determined from their maximum plantarflexion contraction force. Four of the subjects also participated in force matching with the reference force arising from muscle stimulation of the gastrocnemius and soleus causing a non-voluntary plantarflexion twitch contraction at two targets forces.

Results: Force matching error was low across all target forces, and error did not significantly differ between forces. Minimal learning occurred across days and within day across trials. Force matching with stimulation did not appear to differ from voluntary force matching.

Conclusion: Overall, this is the first feasible method for assessing lower limb force matching at the ankle. Eight trials are sufficient to characterize force matching ability in the lower limb. Results indicate that lower limb force perception likely differs in some ways from upper limb force perception.

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Introduction and Background

We interact and move through the world by applying forces on objects or the environment. Understanding how we process and perceive forces starts with the concept of proprioception. Proprioception, defined as the ability to detect sensations about the position and movement of the body and the forces generated by muscles, arises from numerous sensory receptors including muscle spindles, Golgi tendon organs, joint mechanoreceptors, and skin receptors (Proske and Gandevia, 2012.; McCloskey, 1978). Muscle spindles are activated by dynamic stretch within the muscle, while Golgi tendon organs detect muscle tension (McCloskey, 1978). Mechanoreceptors of the joint are activated in response to tissue stress within the joint capsule as well as local compression indicating joint rotation. Skin receptors are activated similarly to the joint receptors, detecting when the skin stretches to contribute to the sensation of movement (Aimonetti, Jean-Marc, et al., 2012; Proske and Gandevia, 2012). Collectively, the sensory feedback is transmitted from the legs and arms to the spinal cord and ascends via the brainstem and thalamus to be processed in the sensory cortex and other brain areas (Proske and Allen, 2019; McCloskey, 1978). The processing of sensory feedback in the brain's sensorimotor network, cerebellum and thalamus provides important information about how much force the muscles and joints are experiencing (McIntyre, 1984; Wegrzyk 2017).

In addition to proprioceptive feedback, evidence indicates force perception also arises as part of the motor command. Motor commands, generated within the motor cortex, act on motorneurons in the spinal cord, and cause a response within the muscle (Proske and Allen, 2019). Importantly, the motor command from the motor cortex projects to other brain areas (e.g., cortex, cerebellum, and brainstem) (Proske and Allen, 2019; McCloskey, 1978). With the addition of centrally processed information, a greater and more sophisticated motor control is achieved (Proske and Gandevia, 2012). While the specific brain location remains unknown, the current consensus is that the motor command and proprioceptive feedback resulting from movement project to a common brain region (Figure 1). Thus, the perception of force is understood to be generated from a combination of central and peripheral afferent information (Proske and Allen, 2019).

Force perception has been most commonly evaluated using a force matching paradigm in the upper limb. Force matching involves asking individuals to feel a specific force and then reproduce that force themselves based on what they felt before. A study assessing force matching with fingers in healthy adults has shown a clear trend of individuals overestimating at low forces and an underestimation when matching higher forces (Cuadra, 2020). Another study that examined wrist flexion force matching also found a similar trend of overestimation and greater error at the lower force targeted (Henry, 2022). Interestingly, one study has examined the ability of healthy adults to reproduce the wrist force generated by brief non-voluntary contractions due to muscle stimulation (Nicolas et al, 2005). This study found that force matching ability was poor and suggests wrist force perception may depend more on the motor command input rather than force-related feedback from the muscle. While there are numerous studies examining of force matching in the upper limbs, a knowledge gap exists in the understanding of force perception in the lower limbs.

The sense of force is critical for motor control when performing simple and complex movements like standing, walking, and running. For example, walking involves correctly identifying the ankle force needed to effectively propel ourselves forward. During walking, ankle propulsion is the primary force moving the body forward, which involves the correct magnitude of muscle contraction from the soleus and gastrocnemius to cause plantarflexion of the ankle

(Awad et al., 2020). However, a general reduction in motor performance with posture and movements like walking are commonly observed with aging. This is likely due to alterations in the sensory feedback from muscles receptors (i.e., muscle spindles and Golgi tendon organs) and the integration of the information they provide in the brain (Henry 2019). Anatomically, there is a reduction in sensory innervations of muscles as well as a decreased number of neurons within the spinal cord also disrupting spinal synaptic integration of sensory feedback (Henry 2019). These age-related changes result in an altered gait and movement patterns characterized by reduced walking speed, shorter stride length and reduced ankle propulsion (Cruz-Jimenez, 2017). When an individual has a stroke, reduced ankle propulsion of the paretic limb is also commonly observed. The lack of ankle propulsion results in the individual walking more slowly and at an increased risk of falling (Awad et al., 2020). The exact reason for why stroke survivors stop effectively using ankle propulsion when walking is unknown. One possible reason for impaired ankle propulsion is that force perception is disrupted due to damage of the motor cortex during stroke and thus motor command input to force perception. An additional explanation is that the stroke causes alterations in how sensory feedback from the ankle muscles is processed in the brain (Chu, 2014).

This study aims to develop a method to quantify ankle force perception that can distinguish the contribution of the motor command and sensory feedback to force perception. This study is a first step towards examining whether ankle force perception is impaired in older adults and persons with stroke and impaired ankle force perception is related to impaired ankle propulsion. Previous studies evaluating the effects of aging on force perception in the upper limb found greater force matching error in older adults compared to young (Henry 2022). Additionally, when assessing force matching in able-bodied adults compared to stroke participants, greater error was observed in the paretic arm compared to the control (Gurari, 2019). To bridge the present knowledge gap of the lower limbs, the three primary objectives of this study are to 1) Characterize force matching ability at five different force levels in able-bodied adults, 2) evaluate whether learning effects occur across repeated force matching trials within session and test-retest reliability across days, and 3) examine force matching ability when the reference force arises from force-related sensory feedback due to muscle stimulation (i.e. lack motor command).

Hypothesis

Objective 1 hypothesis: Based on prior work of upper limb, we hypothesize participants will overestimate forces when matching 10% and 20% of their maximum effort, and they will underestimate at 40 or 50%. The 30% force match level is hypothesized to have the lowest matching force error.

Objective 2 hypothesis: Prior work in the upper limb has suggested 8 trials was sufficient to characterize force-matching ability (Gurari, 2019; McNaughton, 2022), thus we hypothesize minimal learning effects and excellent test-retest reliability.

Objective 3 hypothesis: We hypothesize force matching error when the reference force is from muscle stimulation will differ from the force matching error when the reference force is from voluntary force targeting in able-bodied adults.

Methods

Subjects

Eight subjects ranging between the ages of 20 and 27 years old (4 females and 4 males, weight 74 ± 17 kg and height 1.79 ± .109 m) participated in the study. Participants provided written informed consent in accordance with procedures approved by the Emory University Institutional Review Board.

Equipment

All data were acquired at 2000 Hz using an MP150 acquisition unit (Biopac Systems Inc, Goleta, CA, USA). Surface electromyography (EMG) was recorded from soleus (SOL), medial gastrocnemius (MG), tibialis anterior (TA), and vastus lateralis (VL) muscles with a pair of Ag-AgCl electrodes (2.2 × 3.5 cm; Vermed, Buffalo, NY, USA). Skin was first gently abraded and cleaned with isopropyl alcohol. SOL electrodes were then positioned in the midline of the posterior aspect of the shank just below the gastrocnemius muscle; MG and TA were positioned in the middle of their muscle belly; and VL electrodes were positioned on the distal third of the muscle. EMG signals were amplified, and hardware filtered from 10-1000 Hz (AMT-8, Bortec Biomedical Ltd, Canada). A Delta six-axis force/torque transducers (ATI Industrial Automation, Apex, NC) was used to record plantarflexion force. The sensor was firmly mounted on a rigid such that a foot positioned on a pedal produced a normal force on the sensor with plantarflexion (Figure 2). The force sensor signal was amplified using the factory-calibrated interface (ATI Industrial Automation). Neuromuscular stimulation of SOL and gastrocnemius was completed with STM100C stimulators (Biopac System Inc, CA, USA).

The participant was seated in a chair with back support and the height adjusted so that the knee was flexed 20 degrees. Having the knee at an angle closer to extension and ankle slightly dorsiflexed allowed for minimal contraction of the quadriceps and better engagement of the triceps surae respectively. Additionally, this joint configuration most closely replicates the position of the knee during standing and walking. The foot was placed on the pedal, and the ankle was strapped down to maintain isometric contraction when plantarflexing against the sensor. A monitor was positioned in front of the participants to display visual feedback of the ankle force. At the beginning of each trial, subjects were instructed to ret their foot gently on the pedal; sensor readings were zeroed, so that the sensor measured only active forces.

Electromyography

Surface electromyography (EMG) was used to monitor muscle activity. The soleus and medial gastrocnemius were recorded as they are the main plantar flexors of the ankle. The tibialis anterior was recorded because this muscle acts as antagonist to the triceps surae and will indicate if coactivation occurs during plantarflexion. Additionally, vastus lateralis will be recorded to ensure minimal activation of the quadriceps during ankle plantarflexion.

Maximum Voluntary Isometric Contraction

To record maximal plantarflexion force, the participants were instructed to plantarflex as hard as they could using only their ankle. Verbal feedback was provided when VL activity was observed on the EMG. The analogy of pushing a car pedal was described to better explain the desired movement. The commands "Ready, and go" were given, and verbal encouragement and visual force feedback were provided. Participants stopped pushing when the command "relax" was said. The subjects performed 3 trials of their maximum isometric plantarflexion contraction for a duration of 5 seconds. Rest was allotted between each trial to allow for full recovery. The mean of the three trials determined maximal plantarflexors force and was used to calculate target forces values conditions. The MVIC protocol was repeated at the end of the experiment to ensure subjects were not fatigued due to the testing. In addition to maximum plantarflexion, the maximum dorsiflexion and knee extension were recorded at the beginning of the experiment to identify maximum EMG activity for the tibialis anterior and vastus lateralis muscle. Three trials were recorded for each movement with the same verbal commands as described for plantarflexion.

Voluntary Force Matching

Voluntary force matching included five conditions where the subject was asked to match 10, 20, 30, 40 and 50% of their MVIC force with the right ankle. Each subject repeated 15 trials for the three lower target forces and 8 trials for the two greater target forces. The order of the 10, 20, and 30% was randomized across participants and was always followed by 40 and 50% (Table 1). Subjects were instructed to produce and hold steadily the desired force with verbal and visual feedback of their force and a target line displayed on the monitor screen. The participants were given one to four practice trials to become comfortable and familiarized with the reference force, timing, and verbal instructions given. With the command “Ready and go,” they held the contraction for ten seconds. When the participant believed they achieved and held a steady, constant reference force, they said the word “now” to indicate. When the subject heard “relax,” they stopped and relaxed for two to three seconds. Then, they were asked to reproduce the target force without visual feedback on the screen for another ten second period when they received the instructions “Ready and match” to produce the match force. When they believed they had correctly matched the target force, they said the word “now” to indicate. A trigger was pressed by the researcher to record the timing of both the reference and match force. The participants were reminded to focus on the force being produced by their calf muscles when they pushed.

Multiple measures were taken to eliminate any bias that could change the subject’s perception of force. When viewing the screen for feedback to target the reference force, the subject only saw the number 1 on the y-axis to target instead of the exact force value of newtons. Additionally, the subjects did not receive any feedback on their performance of correctly matching the reference force. Each subject performed these exact methods twice with a minimum of 3 days and a maximum of 11 days in between data collections (Table 1). This was done to evaluate test-retest reliability and determine if there was a learning effect with force matching across days.

Force Matching with Stimulation

To examine the ability of participants to utilize force-related plantarflexion feedback to match a force, subjects were asked to voluntarily reproduce a plantarflexion force produced by electrical stimulation. Two surface electrodes were placed on the gastrocnemius and two surface electrodes were on the soleus to elicit a twitch contraction causing plantarflexion of the ankle. Motor points were found to place the electrodes in the spot where the best muscle contraction can be elicited using the lowest amount of current. The medial and lateral gastrocnemius electrodes were stimulated separately from the two electrodes on the soleus. The cathode was placed on both the medial gastrocnemius and medial soleus. The stimulation parameters included a doublet of two, fifty microsecond pulses with a five millisecond interstimulus interval. The stimulus intensity was adjusted so that the combined gastrocnemius and soleus twitch contractions achieved the desired target force specific to each subject.

The subject completed fifteen trials at target forces of 20 and 10% of their MVIC, which were chosen as a feasible stimulation evoked force levels while also ensuring comfort of the participant. The reference force was produced by a 1.5 second twitch contraction that occurred within a 4 second window. The subject was given two to three seconds of rest before they were asked to match the reference force. They had a ten second window to hold a plantarflexion contraction and match the peak force of the twitch contraction they felt. The subject indicated when they believed to have matched the peak force of the twitch contraction within the time window by saying "now" (Figure 3). The subject was again instructed to focus on their calf muscles throughout the trials. Visual feedback was not provided during the twitch contraction or when attempting to match the electrical stimulation force.

Data Analysis

Data was processed off-line using routines written in MATLAB R2021a (MathWorks, Natick, MA). All force data was low-pass filtered at 10 Hz using a zero-lag, fourth-order Butterworth filter. The reference and matching ankle forces for analysis were extracted from each trial based on participants' identifying when they were steadily holding the reference force and were achieving the matching force, respectively. When the participant said "now," a trigger signal was pressed by the researcher marking the onset of a 1 second data analysis period (Figure 2B). The mean force during the 1 second was calculated for each reference and matching force pair. Constant error (CE), representing force matching accuracy, was computed as the difference between the average values of the forces produced by the reference and match forces ($CE = F_{Match} – F_{Reference}$). For analyzing force matching of muscle stimulation evoked twitch contractions, the peak force produced from the twitch contraction was used to represent the reference force. The matching force was calculated as described above for the voluntary matching trials (Figure 3). A positive constant error value represents an overestimation, and a negative constant error denotes an underestimation. To evaluate if the subjects consistently achieved the reference force and reproduced the matching force, variable error (VE) was calculated as the standard deviation of all the reference, and matching, force trials for each of the target forces. Both constant error and variable error were normalized as a percentage of each subject's MVIC.

Statistical Analysis

Data was analyzed using SPSS Statistical Software. To evaluate the first objective of characterizing force matching at five different force levels, a related-samples Friedman's one-way analysis of variance by ranks test was used (Portney, 2015). The dependent variable was the average CE from the first 8 trials on day 1 for each of the target forces (10, 20, 30, 40, and 50%). This test aimed to determine if the average CE across target forces were statistically different from each other (i.e., over or underestimation of matching).

The second objective aimed to determine whether matching errors were reduced (i.e. learning effect) across days and within days. Test-retest reliability between days for voluntary force matching was examined with Intraclass Correlation Coefficient ($ICC_{(2,k)}$) and between day performance further examined with a paired sample t-test (Portney, 2015; Koo, 2016). The dependent variable used for test-retest reliability was the absolute value of the average CE for the first eight trials from the first day and the absolute value of the average CE for the first eight trials from the second day for each target force. The analysis was also completed comparing the absolute value of the average CE for all fifteen trials from the first day with all fifteen trials from the second day for the first three target forces (10, 20 and 30%) because only 8 trials were recorded for the 40 and 50% target force levels. To examine within day learning effects, the absolute value of the average CE of the first eight trials was compared to the absolute value of the average CE of the last eight trials for each target force on day 1.

For the third objective, the results from force matching with stimulation were compared to the voluntary force matching using descriptive statistics to characterize trends if present. The average CE of the first 8 trials from day 2 of voluntary force matching were compared to the average CE of the first 8 trials when matching muscle stimulation evoked contraction forces for each individual subject for 10 and 20% target forces. Voluntary average CE values from day 2 was chosen because test day 2 was closer in time to the force matching with stimulation session.

Results

Table 2 reports the MVIC values used for each subject on every day of force match testing to calculate the specific target forces. Figure 4 displays the variable error across days for each target force's reference and match force. Subjects successfully achieved a consistent reference force across all target forces and both days. However, this clearly represents the inconsistency when reproducing the matching force, but there is an improvement on day 2 for all five target forces showing that subjects had a more consistent matching force overtime. Variability within the matching force also increased as the target force level increased showing less consistency at 40 and 50% compared to 10, 20, and 30%.

In regard to objective 1, Table 3 reports the average CE of the first 8 trials on day 1 for each subject at each target force as well as the mean across subjects. The highest target force, 50%, showed the lowest mean of average CE which indicates that this force had the lowest error out of the five. Additionally, Figure 5 illustrates the average of all 8 subjects' average CE at each target force, which shows an overestimation at 10, 20, 30, and 40% and an underestimation at 50%. However, the results of the related-samples Friedman's one-way analysis of variance by ranks test yielded a significance value of .791, indicating the average CE across target forces were not statistically different from one another.

The second objective was broken in two parts: learning across days and learning within day. For the first part, Table 4 outlines the results from the Intraclass Correlation Coefficient ($ICC_{(2,k)}$) tests and paired t-tests for each target force between day 1 and day 2. 30% yielded an ICC value indicating excellent test reliability, 10% had a value marking good reliability and 20%

reported a value denoting moderate reliability. On the other hand, 20 and 50% had ICC values reporting poor reliability. 30% had the highest ICC value, but also reported a significant p-value ($p<.05$) revealing a difference between day 1 and day 2. 50% had the lowest ICC value and did not have a significant difference across days. Figure 6 illustrates the average CE across days for each target force allowing visualization of these results. Table 5 and Figure 7 show the results of the second part, learning across trials within day. Table 5 reports the values from the Intraclass Correlation Coefficient ($ICC_{(2,k)}$) tests and paired t-tests comparing the first 8 trials and the last 8 trials for each target on day 1. 10 and 20% had ICC values indicating excellent test reliability. 30% had a lesser ICC value denoting moderate reliability that was complimented by a significant p-value ($p<.05$) showing a difference in the average CE from first 8 trials and last 8 trials. Figure 7 represents these results through a box plot.

With respect to objective three, there was no specific trend indicating if individuals differed in voluntary force matching compared to force matching with stimulation. Tables 6 displays the average CE of muscle stimulation trials and voluntary trials for target forces 10 and 20% from each of the four subjects. Figure 8 allows for the visualization of the data which shows minimal differences between voluntary and muscle stimulation matching trials. There is only one clear outlier, and the cause of the large difference observed in this subject's single target force is unknown.

Discussion

To our knowledge, this was the first study to evaluate a voluntary force matching paradigm at the ankle in able-bodied adults as well as the first to begin examining force matching ability when the reference force arises from force-related sensory feedback due to muscle stimulation in the lower limb. Our observations of individuals following instructions and completing all tasks asked of them without difficulty demonstrate that collecting data from force matching in the lower limb is ultimately feasible. For our first objective to characterize force matching ability at five different force levels, we found overall very low error in force matching ability across subjects. We predicted an overestimation when participants were attempting to reproduce the 10 and 20% target forces which we observed to be correct. However, we also saw an average overestimation of the matching forces at 30 and 40% target force levels and only an underestimation at 50%. Additionally, the lowest matching error was found at the 50% force target when considering the average constant error across participants which was 49.76% (i.e., participants were within 0.5% of the target force). However, we should note that there was more variability at this force target with clusters of 4 persons that overestimated and 4 that underestimated. Overall, even though there were small over and underestimations of matching errors between target force levels, the matching error across target forces were not different from one another indicating a similar performance at each target force across subjects. These findings are not surprising as they correlate with the fact that all of the individuals tested are young and athletic. They all have excellent postural control as well as the ability to walk, run and jump with ease. The lower error is congruent with upper limb force matching findings (Gurari, 2019). However, the lack of significant differences between errors at different target forces does not follow along with trends observed in the upper limb of over matching at lower forces and under matching at higher forces (Cuadra, 2020). This could likely be due to differences in force perception in the upper and lower limb.

Similar to upper limb studies, we can conclude that 8 trials are sufficient to characterize force matching ability in the lower limb (Gurari, 2019; McNaughton, 2022). When comparing the first 8 trials with the last 8 trials, all ICC values reported moderate to excellent test reliability at 10, 20, and 30% despite having a significant difference in 30%. Because of the ICC results, we can conclude only 8 trials should be enough to understand force matching abilities. On the other hand, across day 1 and day 2, 10, 30, and 40% found moderate to excellent test reliability. 20 and 50% had poor test reliability, which is likely due to the fact that there were differences between days that did not have a trend across subjects. Specifically at 50%, about half of the subjects went from underestimating to over and the other half switched from overestimating to under. However, the results from the paired t-test are not significant, because when only looking at the absolute value of the constant error, subjects were on average not getting closer to target force on day 2. In regard to 30%, the target force with the highest ICC value, every subject improved across days but only by very small amounts.

One potential limitation of the study was the difference in MVIC values across days. Across subjects there was about an 80N increase between day 1 and day 2 for their MVIC average of three trials. This made the target forces across days different from one another, which could have influenced learning across days. Subjects could have potentially performed differently on the second day if the target force was exactly the same. Another potential limitation of the study was the small sample size of eight for voluntary force matching as well as only four participants for matching with stimulation. ICC results could have reported higher reliability if there was a larger sample size to show clearer trends. There were no statistical tests performed with the force matching with stimulation data due to the very small sample size. Observational results could have been solidified by statistical values to make conclusions stronger.

We hypothesized that force matching error when the reference force is from muscle stimulation will differ from the force matching error when the reference force is from voluntary force matching, which was not supported by the data. From the use of descriptive statistics, we found subjects performed quite similarly to their voluntary force matching average CE with force matching with stimulation. The upper limb study that examined wrist force generated by non-voluntary muscle stimulation contractions found opposite results of subjects matching muscle stimulation forces very poorly. This is also likely due to the fact that force perception is different between the upper and lower limb. The use of muscle stimulation force in our case removes the motor command from the force perception equation and forces the participant to mainly rely on sensory feedback. This could lead to the notion that lower limb force perception relies more heavily on sensory feedback in comparison to the upper limb relying more on the motor command.

Results from both objective one and objective three lead to the same conclusion: upper limb and lower limb force perception differ from one another in some ways. Anatomically, it is well known that the upper limb has a larger relative area represented in the primary motor cortex compared to the lower limb (Nguyen, 2023). The anatomical representation differences are believed to reflect differences in the functional tasks for which the upper and lower limb often engage. The upper limbs are often manipulating and interacting with objects using fine motor dexterity that appear to require greater cortical influence. In contrast, the lower limbs generally interact with the ground in order to manipulate our body for locomotion. While proprioception is important for task completion in the upper and lower limbs, the less cortical representation of the lower limb suggests the possibility that sensory feedback likely plays a larger role in lower limb movement and tasks. Therefore, the difference in functionality and representations in the brain between the upper and lower limb supports the idea that they likely differ in force perception as well.

To continue testing the contributions of sensory feedback and the motor command, a ballistic force matching paradigm could be tested to evaluate the role of the motor command in lower limb force perception without sensory feedback. This involves a single rapid force plantarflexion contraction with visual feedback as the reference force followed by the same movement without visual feedback as the match force. This requires subjects to mainly rely on the motor command to effectively match the reference force. Taking another step forward to test the contributions of sensory feedback and the motor command to force perception, the reference force could be produced by the same muscle stim twitch contraction as this study but matched with the single, rapid ballistic contraction. This paradigm would give the subject very little information to accurately replicate the reference force when matching. Both of these tests have been piloted but not yet analyzed. Further analysis and more subjects will provide a clearer understanding of feasibility of the force matching test and trends of the results.

As these older adults and stroke survivors served as motivation for this study, a feasible future direction is to complete testing in older adults (65 years or older) and stroke survivors. Greater error in voluntary force matching was observed in both of these groups compared to able-bodied individuals in upper limb force matching studies (Henry, 2022; Gurari, 2019). We would predict that results would be similar in the lower limb due to the altered gait observed in both populations. However, conclusions from this study suggest that lower limb testing could yield different results from upper limb studies.

Future analysis can be done to provide a clear story of muscle activation during the voluntary force matching paradigm. The contributions of the gastrocnemius and soleus can be evaluated to see if one plays a larger role in plantarflexion than the other. Their roles could also change at different target force levels. Assessing if there is any coactivation of the tibialis anterior during plantarflexion would be important to the whole story of force perception. If there is activation of the TA during plantarflexion, then the soleus and gastrocnemius must contract more to counteract their antagonist. This could change the way individuals are perceiving the forces generated by their muscles to plantarflex the ankle.

Overall, our results demonstrate the need for further investigation of lower limb force perception assessment. This study contributes the first feasible method for assessing lower limb force matching at the ankle. Our results characterize how able-bodied individuals perceive and reproduce plantarflexion forces. This is a first step toward examining whether ankle force perception may influence how people move and interact with the world. More importantly, this methodological approach will enable future work to examine how whether impairments in ankle force perception are related to walking impairments commonly observed due to aging and neuropathology.

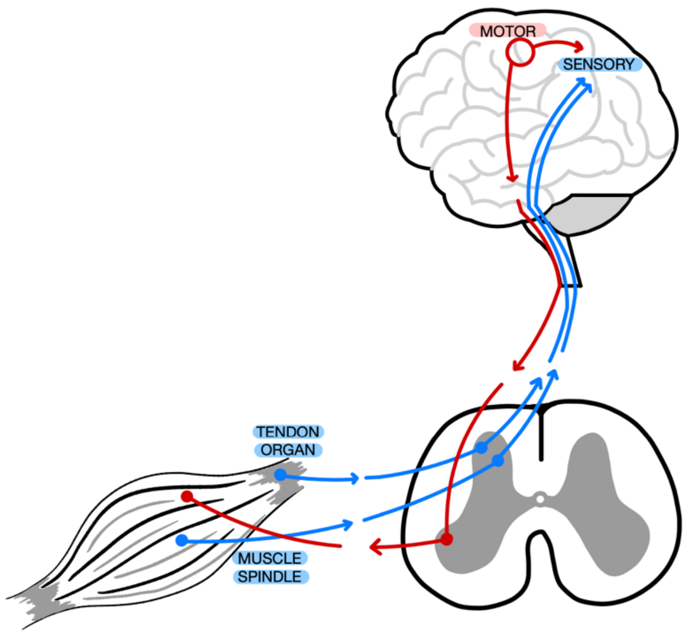

Figure 1. A sketch diagram illustrating the combination of sensory feedback and the motor command that comprises force perception. The sensation of stretch from the muscle spindle fibers and detection of tension within the muscle from the Golgi tendon organs (represented as blue lines) are sent through the spinal cord and up to the brain to be processed. The motor command (represented as red lines), generated within the motor cortex, has a projection that combines with sensory feedback as well as projects down through the spinal cord to the muscle.

Table 1. Subject participation details and order of target forces during experiment

Subject	Age	Height (m)	Sex	Days between	Order of target forces
1	22	1.72	F	11	10, 30, 20, 40, 50
2	20	1.62	F	3	10, 20, 30, 40, 50
3	21	1.75	F	7	20, 10, 30, 40, 50
4	21	1.70	F	4	30, 20, 10, 40, 50
5	22	1.85	M	7	10, 20, 30, 40, 50
6	21	1.87	M	3	20, 10, 30, 40, 50
7	27	1.95	M	7	30, 20, 10, 40, 50
8	22	1.85	M	3	20, 10, 30, 40, 50

*Subjects 01, 03, 05 and 07 participated in day 3 of force matching with stimulation

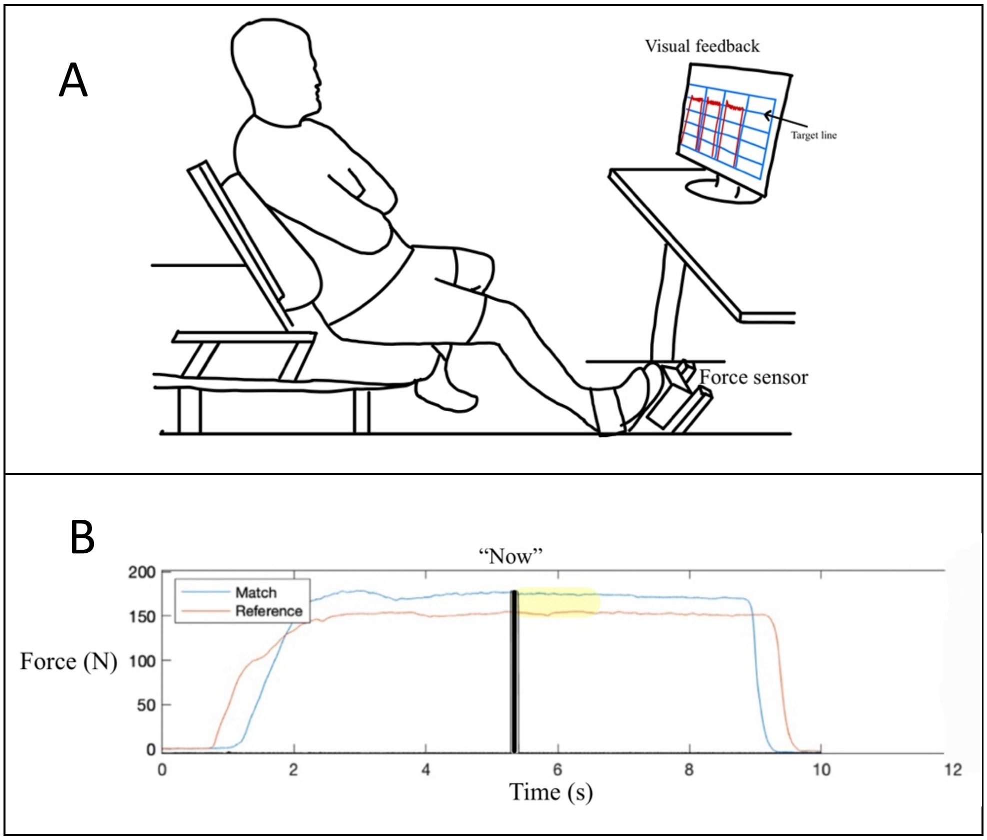

Figure 2. Experimental Setup and Voluntary Force Matching A: An illustration of the apparatus and setup. B: A representation of the reference and match forces from the voluntary force matching condition. The reference force is reflected in both images by a red line seen by the researcher and participant. The blue represents the match force produced by the subject, but only seen by the researcher. The black bar denotes the trigger when the subject verbally said "now" indicating they have effectively matched the reference force. The highlighted portion is the one second of force that is averaged to calculate constant error.

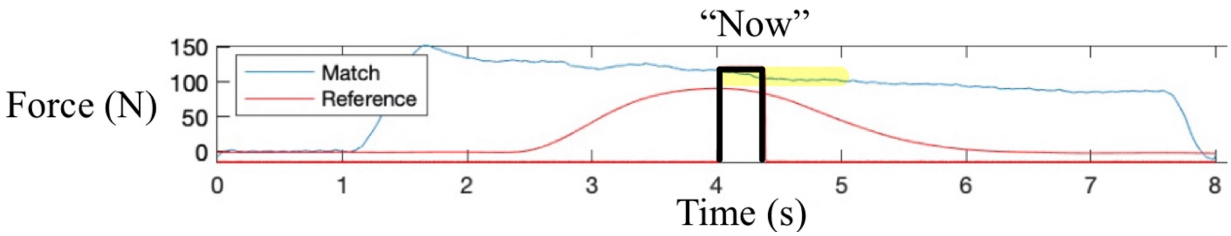

Figure 3. Force Matching with Stimulation. The reference force from stimulation is shown in red, and the voluntary match force is represented by the blue. The reference muscle stimulation force is a four second window that has been stretched to compliment the eight second match force. Both forces are only seen by the researcher. The black bar denotes the trigger when the subject verbally said "now" indicating they have effectively matched the peak of reference force. The highlighted portion is the one second of the match force that is averaged to calculate constant error with the peak reference force.

Subject	MVIC Day 1	MVIC Day 2	MVIC Day 3
1	325	492	464
2	290	373	
3	643	661	620
4	577	658	
5	817	882	830
6	648	732	
7	827	932	932
8	885	940	

Table 2. MVIC values of each subject for each day of force match testing used to calculate target forces.

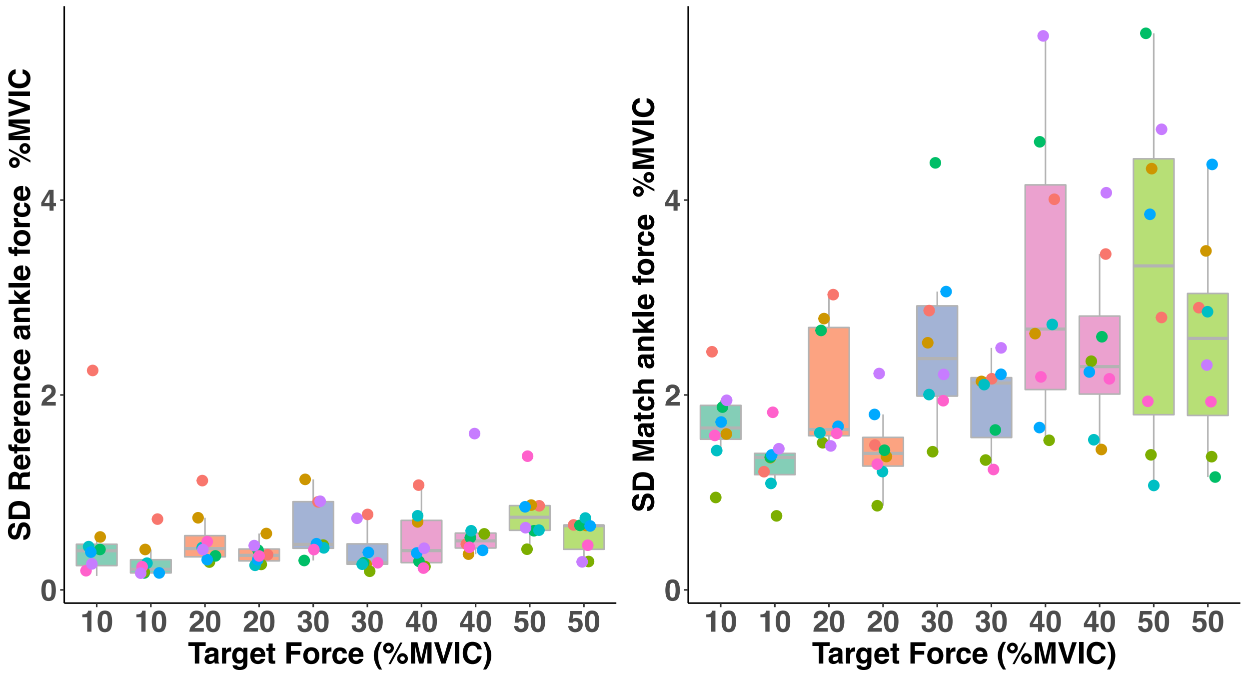

Figure 4. VE values of day 1 and day 2 reference and match forces.

Average CE	10%	20%	30%	40%	50%
Subject 1	2.55	4.86	3.9	4.96	3.95
Subject 2	-0.6	-3.3	-1.4	-5.26	2.25
Subject 3	1.41	2.6	0.92	1.26	-1.85
Subject 4	4.97	3.47	5.64	5.1	-5.98
Subject 5	1.4	1.82	1.74	2.09	2.27
Subject 6	0.52	0.99	3.59	-2.36	-2.8
Subject 7	0.64	0.07	0.84	6.24	-1.7
Subject 8	-0.5	1.11	1.46	-0.36	1.94
Mean	1.29	1.45	2.09	1.46	-0.24

Table 3. Objective 1 Data. The average constant error (CE) of the first 8 trials on day 1 for each subject at each target force and the mean across subjects to characterize force matching at each target force.

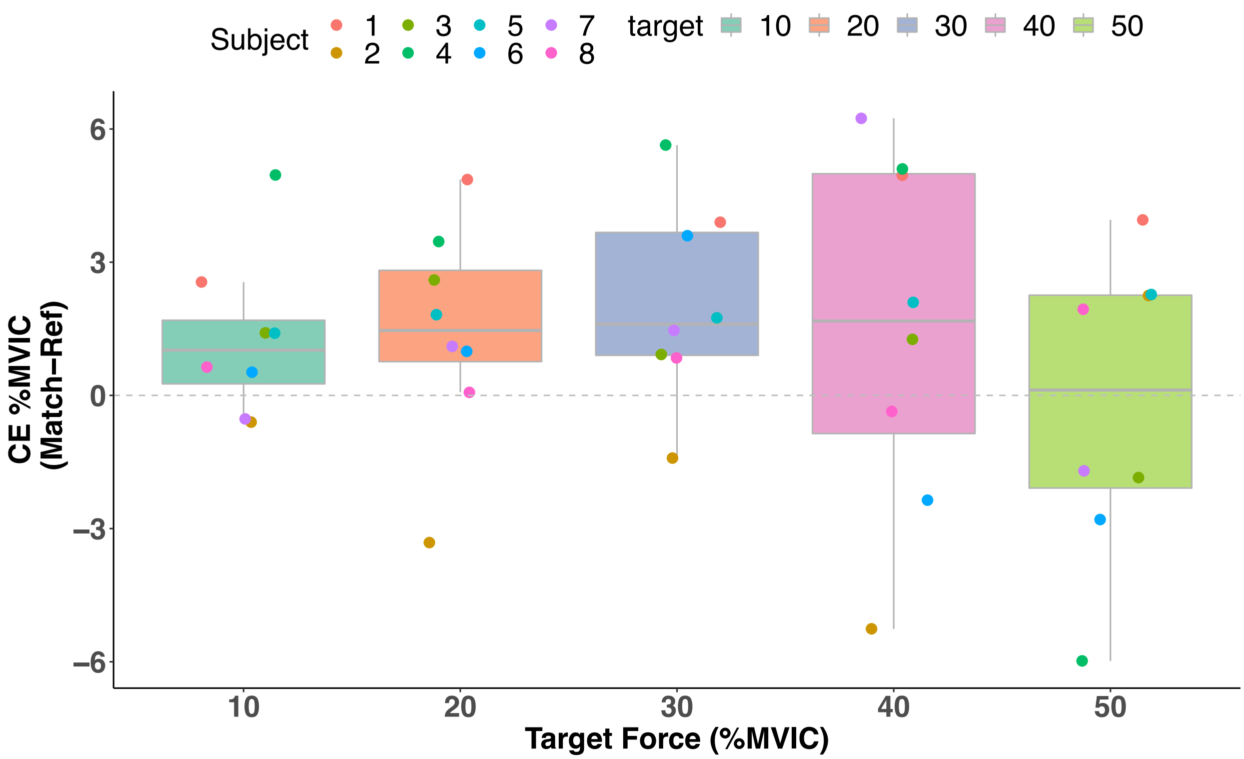

Figure 5. Objective 1 data. The average of all 8 subjects' average CE at each target force illustrating an overestimation at 10, 20, 30, and 40% and an underestimation at 50%.

Target force	ICC value	Two-sided p value
10	0.816	0.864
20	0.408	0.476
30	0.946	0.001*
40	0.701	0.352
50	0.144	0.388

Table 4. Objective 2 determining learning across days data. The results from Intraclass Correlation Coefficient ($ICC_{(2,k)}$) tests and paired sample t-tests for each target force. * denotes a significant value ($p<.05$).

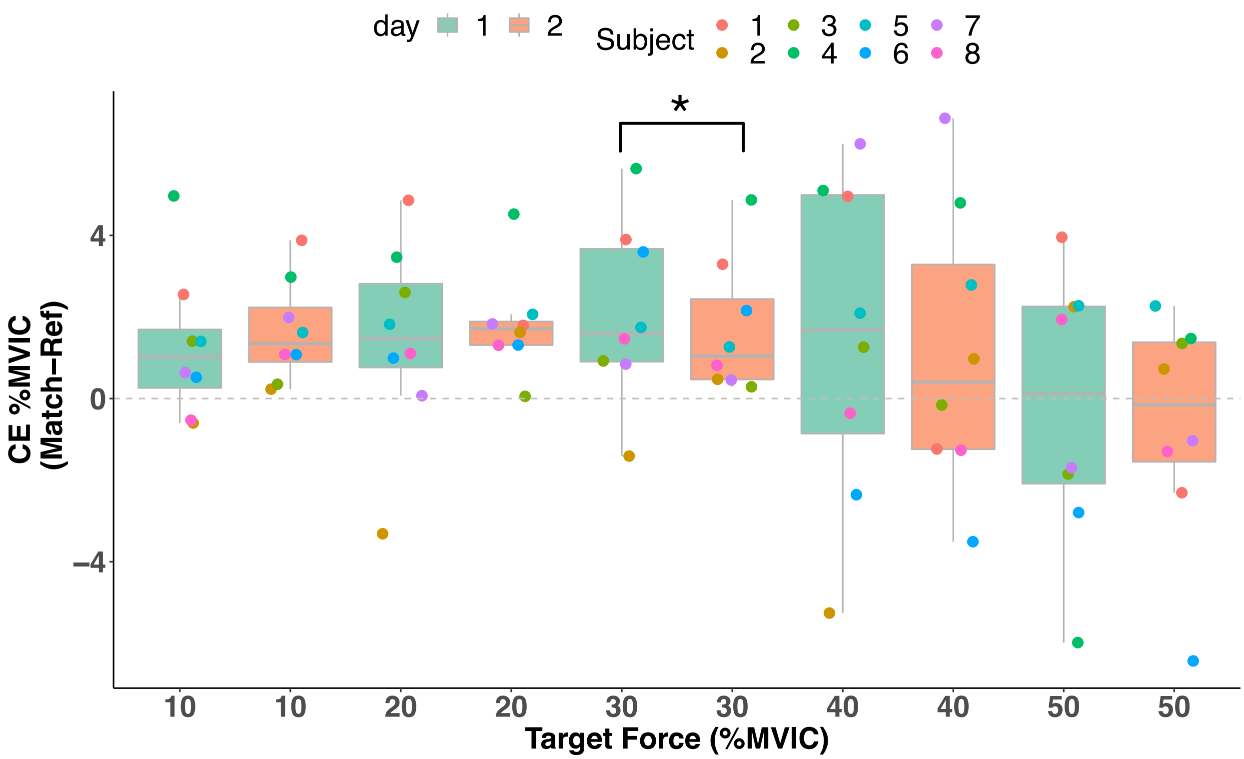

Figure 6. Objective 2 determining learning across days data. The average CE across subjects from day 1 and day 2 for each target force. * denotes a significant difference between day 1 and day 2 (p<.05).

Target force	ICC value	Two-sided p value
10	0.934	0.062
20	0.919	0.984
30	0.706	0.008*

Table 5. Objective 2 determining learning within day data. The results from Intraclass Correlation Coefficient ($ICC_{(2,k)}$) tests and paired sample t-tests for each target force. * denotes a significant value ($p<.05$).

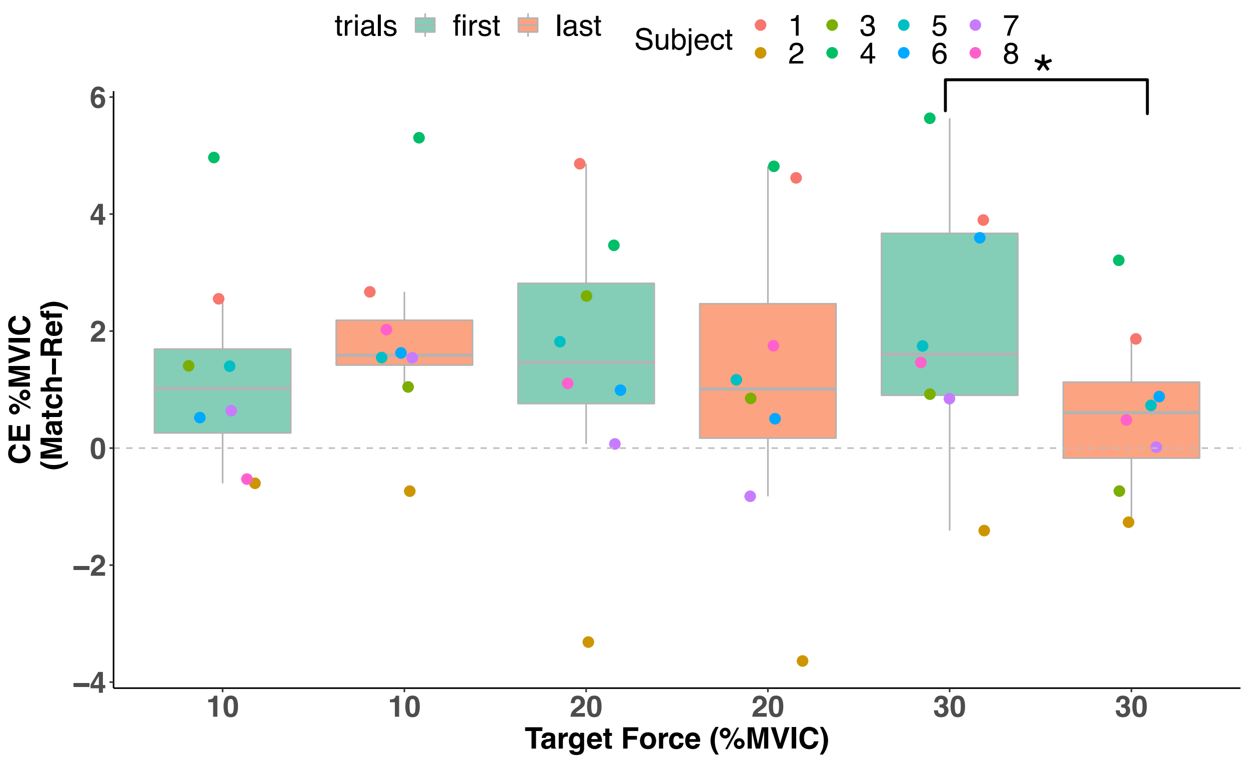

Figure 7. Objective 2 determining learning within day data. The average CE across subjects from the first 8 trials and the last 8 trials for target forces 10, 20, and 30%. * denotes a significant difference between the first 8 trials and the last 8 trials.

Average CE	10% Muscle Stim	10% Voluntary	20% Muscle Stim	20% Voluntary
Subject 1	0.36	3.88	-0.31	1.79
Subject 3	-1.00	0.35	-2.90	0.05
Subject 5	3.78	1.62	20.11	2.06
Subject 7	4.37	1.08	4.02	1.31

Table 6. Objective 3 Data. The average CE of the first 8 trials for both muscle stimulation and voluntary force matching for the four subjects that completed force matching stimulation at 10 and 20%.

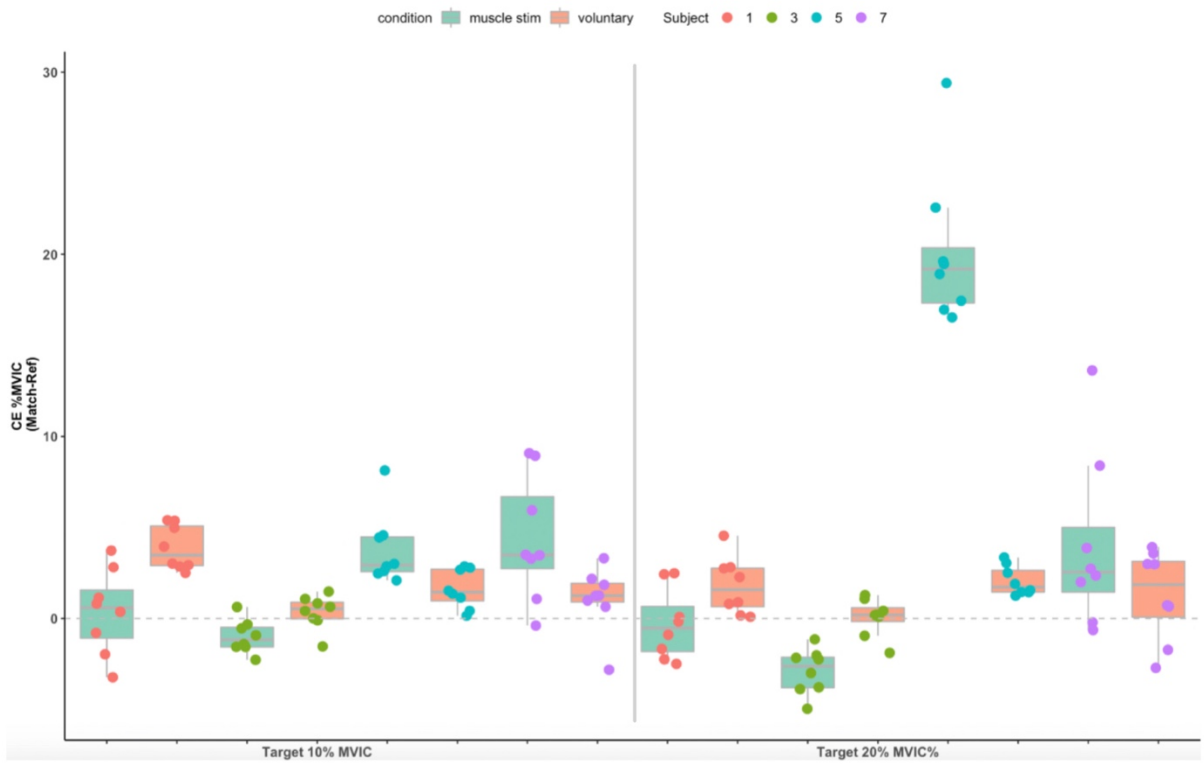

Figure 8. Objective 3 Data. The average CE of the first 8 trials for both muscle stimulation and voluntary force matching for each of the four subjects that completed force matching stimulation at 10 and 20%.

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