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Sense of Effort Determines Lower Limb Force Production During Dynamic Movement in Individuals With Poststroke Hemiparesis

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Objective. This study's purpose was to determine if individuals who have had a stroke primarily use sense of effort to gauge force production during static and dynamic lower limb contractions. If relying on sense of effort while attempting to generate equal limb forces, participants should produce equal percentages of their maximum voluntary strength rather than equal absolute forces in their limbs. *Methods.* Ten stroke participants performed isometric and isotonic lower limb extensions on an exercise machine. *Results.* When participants attempted to produce equal bilateral isometric forces, there was a significant difference in absolute force between limbs (ANOVA, $P < .0001$) but no significant difference when force was normalized to each limb's maximum voluntary contraction (MVC) force ($P = .5129$). During bilateral isotonic contractions, participants produced less absolute force in their paretic limb ($P = .0005$) and less relative force in their paretic limb (normalized to MVC force) when participants were given no instructions on how to perform the extension ($P = .0002$). When participants were instructed to produce equal forces, there was no significant difference between relative forces in the 2 limbs ($P = .2111$). *Conclusions.* For both isometric and isotonic conditions hemiparetic participants relied primarily on sense of effort, rather than proprioceptive feedback, for gauging lower limb force production. This outcome indicates that sense of effort is the major factor determining force production during movements. Lower limb rehabilitation therapies should not only train strength in the paretic limb but should also train patients to recalibrate force-scaling abilities to improve function.

Keywords: *Muscle; Sense of effort; Stroke*

Humans control force production in their limbs by using an internal model of musculoskeletal mechanics to calculate appropriate neural signals.[1-3] The model allows the nervous system to generate predicted sensory information from the neural command and compare it to the sensory information from the actual movement. As a result, motor commands depend on the nervous system's understanding of system mechanics and comparisons of predicted and actual afferent sensory feedback. As individuals learn a task, they update their internal model to generate a better prediction of the actual motion.[4]

Fine control of upper limb force production is a motor task that likely uses an internal model to set efferent commands. Humans use a neural representation of their musculoskeletal system to help them determine the correct efferent commands to produce a desired motion. Individuals need to have a good internal model if they are to produce a desired force level. The internal model not only allows humans to produce accurate efferent commands but also helps in interpreting proprioceptive feedback. In generating muscle force, humans can use both the scaling of the descending motor command, generally termed sense of effort,[5] and the ascending sensory information, termed sense of force or tension.[6]

Studies involving contralateral limb-matching paradigms have been used to determine how humans perceive muscle force and whether or not they depend more on sense of effort or sense of force. In a contralateral limb-matching protocol, participants develop force in 1 limb (the reference limb) and through use of visual force feedback they are asked to reach a target force level. Once they reach the target force level with the reference limb they begin producing force with their contralateral limb (the matching limb). Participants do not receive any visual feedback regarding force in the matching limb.

If the mechanical output of an upper limb muscle is altered through fatigue,[7-9] partial curarization,[10] or through changes in muscle length,[11] individuals often overestimate the force produced in that limb. Results from upper limb studies of isometric elbow flexion/extension on neurologically intact participants with 1 limb in a state of fatigue showed that participants did not produce forces of equal magnitude in their limbs.[7,8,12,13] Participants consistently produced less force in the

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fatigued limb, indicating they were overestimating force in the limb. When individual limb forces were normalized to the postfatigue maximum strength of each limb directly before testing, these normalized forces did not show any significant differences between limbs.[7] These results led Carson et al[7] to conclude that when participants attempt to produce equal forces in their limbs they produce equal percentages of each limb's maximal voluntary strength rather than equal absolute forces.

Results from a lower limb study on the force asymmetry of neurologically intact individuals showed similar results. Participants included in this study possessed a greater than 10% force discrepancy in bilateral foot forces during maximum voluntary contraction (MVC) trials. Participants attempting to produce equal forces in their lower limbs during an isometric lower limb extension did not produce equal magnitudes of force.[14] Instead, participants produced equal percentages of their bilateral (not unilateral) maximum voluntary strength in each lower limb. These studies suggest that neurologically intact participants primarily use a sense of effort originating from a corollary discharge of the motor command to the muscles,[5,14-16] rather than relying on proprioceptive feedback to gauge force production in their limbs.

In neurological populations, such as individuals who have had a stroke, hemiparesis affects patients' abilities to approximate force production in their limbs. Proprioception is affected poststroke, suggesting that these individuals may also rely more on their sense of effort compared with sense of force. Previous studies have demonstrated that individuals with complete loss of proprioceptive sensory abilities still have a good sense of effort and use sense of effort to gauge force production.[17,18] During isometric submaximal upper extremity matching tasks, stroke participants consistently overestimate forces produced in the paretic limb, even though maximum voluntary force trials reveal that they have the ability to produce forces of equal magnitude.[19,20] Because the stroke participants have reduced maximum force ability in the paretic limb, determining muscle activation based on a fixed proportion of maximum force capability will result in less force in the paretic limb. It is possible that individuals may not update their internal model of musculoskeletal mechanics to account for their poststroke weakness.[21]

Individuals' inability to account for poststroke hemiparesis and produce appropriate force levels with their paretic limb affects their ability to stand from a seated position, perform transfers, and ambulate, which may predispose a patient to falls. A mismatch between expected force production and actual force production in these situations can have serious implications for movement. Previous studies have examined force production and perception in simplified tasks of upper extremity isometric contractions.[19,20] Mobility tasks, however, involve force production in the lower limbs during dynamic movements.

In this study, we have investigated force production in the lower limbs of individuals with poststroke hemiparesis, both during isometric and isotonic movements. Results from these 2 experiments will provide insight into whether or not control of force in stroke participants is the same for static and dynamic movements. The goal of this study was to determine if force asymmetry during isometric and isotonic bilateral force production of individuals with poststroke hemiparesis both result from neural mechanisms related to sense of effort. We hypothesized that hemiparetic participants attempting to produce equal forces in their lower limbs would generate equal percentages of their bilateral maximum voluntary strength rather than equal absolute limb forces during both isometric and isotonic movement.

Methods

Subjects

We recruited 10 individuals with stroke-induced hemiparesis (5 men and 5 women; ages 56 ± 7.3 years, mean ± SD) (Table 1). Inclusion criteria consisted of individuals (1) at least 6 months postonset of a single neurologic insult that included ischemic or hemorrhagic type strokes (verified through MRI or CT scan data from patients' medical records); (2) between the ages of 18 and 85 years; (3) free of any musculoskeletal injuries or deformities; (4) presented with no spastic hypertonia in the lower limbs; and (5) adequately able to comprehend our instructions. A physiatrist at the University of Michigan evaluated and cleared each individual for participation in the study. All participants gave written informed consent approved by the Institutional Review Board for Human Subject Research at the University of Michigan Medical School. One individual (subject 6) participated in the study but his data were excluded from the analysis because he had great difficulty remembering and following the instructions. A physical therapist evaluated participants' lower extremity physical performance with the lower limb and balance portions of the Fugl-Meyer Clinical Assessment scale (Table 1). The authors noted various sensory deficits based on comments from the participants including reduced cutaneous sensation and impaired force perception. No participants reported impaired sense of limb motion and position.

Experimental Design

We performed 2 experiments to investigate the ability of individuals with poststroke hemiparesis to match forces between their lower limbs during static and dynamic force matching tasks. We performed maximum strength testing and 2 force matching experiments within 1 single testing session. Participants received extended breaks of at least 15 minutes between all sections of the data collection.

For the entire study, participants exercised on a robotic exercise machine built in the University of Michigan's Human Neuromechanics Laboratory[22] (Figure 1). Participants were

Table 1
Subject Characteristics

Subject	Age, Years	Gender	Paretic Side	Postonset, Months	Type of Stroke	Lesion Location	Fugl-Meyer[a] Lower Extremity	Fugl-Meyer[a] Balance
1	69	M	L	7	Right MCA (occipital-parietal regions)	Ischemic	32	4
2	50	M	R	36	Left MCA	Ischemic	25	11
3	52	M	L	20	Right parietal lobe	Ischemic	23	10
4	69	F	R	12	Left hemisphere	Ischemic	23	8
5	50	F	L	39	Right MCA	Ischemic stroke secondary to large vessel atherosclerosis	26	10
6[b]	55	M	L	32	Right hemisphere	Ischemic	na	na
7	53	F	R	10	Left pons	Ischemic	27	11
8	51	F	R	39	Left frontal lobe	Ischemic	14	9
9	53	M	R	8	Left occipital and parietal lobe	Embolic	34	14
10	58	F	L	37	Temporal lobe	Ischemic	18	7

Abbreviations: M, male; L, left; MCA, middle cerebral artery; F, female; R, right; na, not available.

[a] Fugl-Meyer Clinical Assessment scale: lower extremity motor score (0-34), balance motor score (0-14).

[b] Subject 6's data were excluded from analysis because he had great difficulty remembering and following the instructions.

supine on the exercise machine and placed their feet on a vertical dual force platform (Model Dual Accu-Gait, AMTI, Watertown, Massachusetts). We used foot straps to stabilize their feet.

Maximum Strength Testing

We recorded participants' isometric (static) and isokinetic (dynamic) strength on the exercise machine. We assessed participants' isometric strength with the machine in isometric mode. In isometric mode, the motor was turned off and the sled was locked into position such that the participant was halfway between the sled position of 90-degree knee and hip flexion and complete extension of the lower limbs. We assessed participants' isokinetic strength with the robotic exercise machine in isokinetic mode. In isokinetic mode, the computer controlled resistance so that movement velocity remained constant at 15 cm/s during lower limb extensions. If a participant pushed hard and therefore the sled moved faster, the controller increased resistance to maintain the reference velocity. During operation of this mode, participants received visual feedback only of movement timing (ie, when to start and stop pushing). We instructed participants to only push during the extension phase and relax during the flexion phase. Participants began in a flexed position with their knee and hip angles at approximately 90° and then extended their lower limbs completely being careful to not lock out their knees.

For both static and dynamic strength testing, we quantified participants' maximum force ability with 2 trials each of bilateral, nonparetic limb only, and paretic limb only MVCs. We randomized the trial order and verbally encouraged participants to push as hard as they could with either 1 foot or both feet throughout each movement. We allowed participants to rest as long as necessary between each MVC trial (no less than 3 minutes).

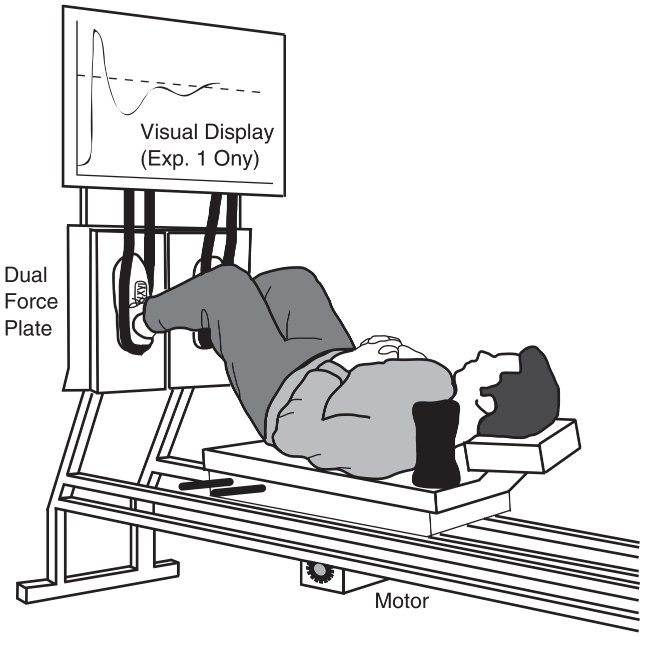
Experiment 1: Isometric

The protocol for experiment 1 was previously used to investigate neurologically intact participants' lower limb force matching ability.[14] Participants performed 2 trials of isometric lower limb force matching in isometric mode. Participants exerted a force equal to 35% of the paretic limb isometric bilateral MVC force. This level was chosen because it represented a force level that was achievable by each participant. Individuals received visual feedback of only the target force level and the amount of force applied by the nonparetic limb. When participants reached the target force level in the nonparetic limb, we instructed them to begin applying force with the paretic limb. No feedback was given regarding the paretic limb force. Participants verbally signaled to the experimenter once they believed they had matched forces in both lower limbs. On this verbal cue, participants held the isometric contraction for 2 seconds and then relaxed. Participants rested 2 to 3 minutes between trials.

Experiment 2: Isotonic

Participants performed 2 sets of 6 lower limb extensions in isotonic mode. In isotonic mode, the resistance for continuous lower limb extensions remained constant. We instructed participants to extend their lower limbs completely (not locking out their knees), flex to a knee and angle of approximately 90°, and match their movement speed to a metronome set at 0.33 Hz. Participants performed both sets against a total constant resistance equal to 80% of the peak force produced by the paretic limb during the isokinetic bilateral MVC (ie, with symmetric forces, a total resistance level of 80% would be equivalent to the paretic limb producing 40% of its MVC force). This resistance value was chosen such that it ensured that participants had the capacity for equivalent forces

Figure 1
Individual With Poststroke Hemiparesis Using the Leg Press Exercise Machine



Note: Participants reclined on the machine and placed their feet in foot straps onto a dual force platform. In experiment 1, a visual display allowed participants to receive force feedback of the target force (dashed line) and nonparetic limb force (solid line). In experiment 2, we removed the visual display and activated the motor to control resistance.

throughout the extensions even if the resultant forces were not equal. In set 1, no instructions were given to participants on how to perform these extensions (no force instruction). In set 2, we instructed participants to attempt to produce equal forces throughout the entire movement and verbally reminded them throughout the trials (produce equal forces).

Data Acquisition and Analysis

For both experiments, we recorded individual lower limb forces from dual force plate data (Figure 1) sampled at 1000 Hz. Each limb's MVC force, both isometric/isokinetic and unilateral/bilateral, was determined as the maximum force measured during the 2 trials.[8,12] For isometric force matching trials, we calculated average foot forces applied during the 2 seconds following the participants' verbal cue. For isotonic force matching trials, we identified cycle timing from motor encoder data and averaged foot forces across only the extension phase of the cycle. For all force matching trials, we normalized the averaged forces to each limbs' unilateral maximum force ability and separately to bilateral maximum force ability to determine the amount of effort participants used in each limb.

We performed a repeated measures ANOVA (participant by limb by condition) to test for significant differences in lower limb MVC forces during bilateral and unilateral conditions for both isometric and isokinetic data (JMP IN software, SAS Institute, Inc, Cary, North Carolina). For both experiments we used a repeated measures ANOVA (participant by limb) to test for differences in absolute lower limb forces, as well as forces normalized to unilateral and bilateral MVC force. When the ANOVA showed significant differences ($P < .05$), we used Tukey-Kramer Honestly Significant Difference (THSD) post hoc tests to further delineate differences ($P < .05$). Post hoc power analyses were carried out where appropriate.

Table 2
Peak Force Recorded During Isometric and Isokinetic Maximum Voluntary Contractions

Condition	Nonparetic Limb Peak Force (N)	Paretic Limb Peak Force (N)
Isometric MVC		
Unilateral	1107 ± 143	738 ± 132[a]
Bilateral	901 ± 176	629 ± 115[a,b]
Isokinetic MVC		
Unilateral	604 ± 101	491 ± 94[a]
Bilateral	593 ± 89	379 ± 83[a,b]

Note: Values are mean ± sem. MVC, maximum voluntary contraction.

[a] Post hoc (THSD) analysis indicates significant decrease in paretic limb force compared with nonparetic limb force within a condition ($P < .05$).

[b] Post hoc (THSD) analysis indicates significant decrease in bilateral peak force compared with unilateral peak force within a limb ($P < .05$).

Results

Maximum Strength Testing

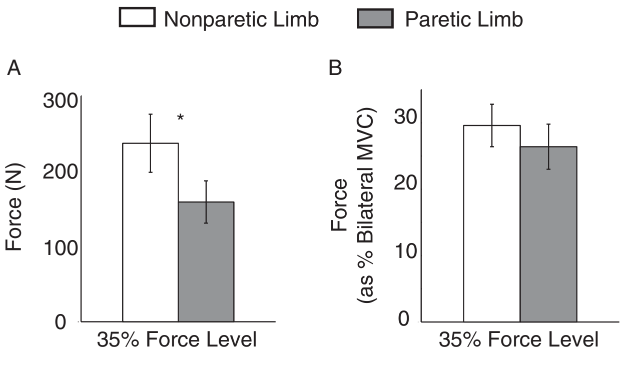
Bilateral isometric MVC trials showed significant differences between limbs (ANOVA, $P < .0001$) (Table 2). Peak paretic limb forces were significantly lower than nonparetic by 30% during bilateral isometric MVC conditions (THSD, $P < .05$). A significantly lower peak force was recorded within the paretic limb during the bilateral compared to the unilateral isometric MVC condition (THSD, $P < .05$).

During isokinetic lower limb extensions, bilateral MVC trials showed significant differences between limbs (ANOVA, $P < .0001$) (Table 2). Peak paretic limb forces were significantly lower than nonparetic by 36% during bilateral isokinetic MVC conditions (THSD, $P < .05$). A significantly lower peak force was recorded within the paretic limb during the bilateral, compared to the unilateral isokinetic MVC condition (THSD, $P < .05$).

Experiment 1: Isometric

Participants were able to produce the target force with their nonparetic limb through use of visual feedback but did not produce a force equivalent in magnitude in their paretic limb. Average force data showed that all participants produced less absolute force in the paretic limb when compared with

Figure 2
Experiment 1: Average Forces During Isometric Force Matching Trials



Note: The target force level was set to 35% of the paretic limb peak force during the bilateral isometric maximum voluntary contraction (MVC) condition. White columns represent nonparetic limb forces and gray columns represent paretic limb forces. A, Absolute force shows significant difference between limbs (ANOVA, $*P < .0001$). B, Force normalized to bilateral MVC shows no significant difference between limbs (ANOVA, $P = .5129$). Error bars are standard error of the mean.

the nonparetic limb (ANOVA, $P < .0001$) (Figure 2A) even though participants believed the forces between their limbs were equal.

Normalizing force data to each limb's bilateral isometric MVC peak force resulted in no significant differences between limbs (ANOVA, $P = .5129$) (Figure 2B). The normalized force data (Figure 2B) indicate that the paretic limb undershot the target as the 35% force level was not achieved. Since the nonparetic limb's MVC force was greater than the paretic limb's MVC force, achieving the target force in the nonparetic limb equaling less than 35% MVC force in this limb. Post hoc analyses revealed a least significant value of 1.96. This indicates that if there was a real difference between limbs that we did not have the power to detect, there is a 95% chance that it is no larger than 1.96% of the bilateral MVC value.[23] Even if there is a type 2 error, the magnitude of the difference is small.

Experiment 2: Isotonic

Example force profiles of 4 participants with poststroke hemiparesis performing isotonic lower limb extensions are shown in Figure 3. Compared to the no force instruction condition, when participants were instructed to produce equal forces in their limbs their production force ranged from generating even less force in their paretic limb to 1 participant producing extremely large forces in their paretic limb. Overall participants produced less absolute force in the paretic limb than in the nonparetic limb during both the no force instruction condition and the produce equal forces condition (ANOVA, $P < .0001$ and $P = .0002$, respectively) (Figure 4A). Intersubject variability of the movement timing was 0.34 Hz ± 0.021 Hz for the no force instruction condition and 0.33 Hz ± 0.011 Hz for the produce equal forces condition.

Normalizing force data to each limb's bilateral isokinetic MVC peak force resulted in a significant difference between limbs for the no force instruction condition (ANOVA, $P = .0005$) and no significant difference for the produce equal forces condition (ANOVA $P = .2111$) (Figure 4B). Post hoc analyses revealed a least significant value of 2.69. Thus, if there is a real difference between limbs, there is a 95% chance it is no larger than 2.69% of the bilateral MVC value.[23] Even if there is a type 2 error, the magnitude of the difference is small.

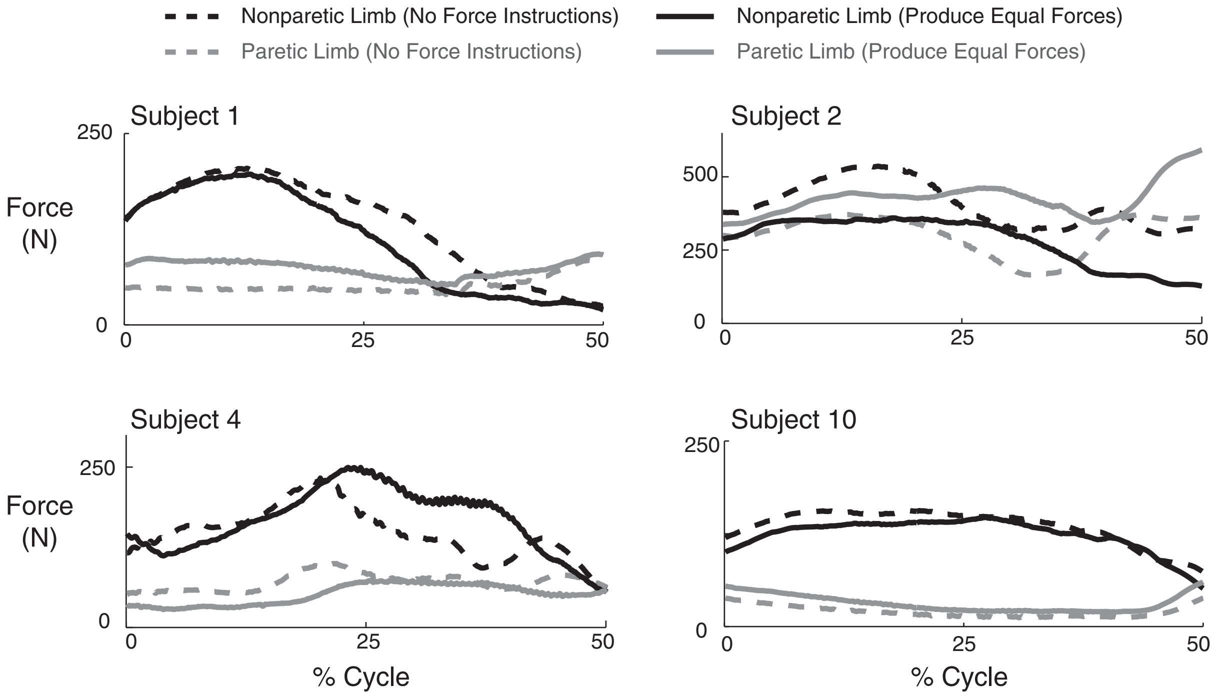
Discussion

Our findings indicate that, similar to the upper limbs, control of force production in individuals with poststroke hemiparesis is similarly reliant on sense of effort for lower limbs. During the isometric force matching of experiment 1, participants consistently produced less force in their paretic limb even though the target force was set low enough that participants had the capability for equal forces. Normalizing forces to each limbs' bilateral isometric MVC force revealed no significant differences between limbs suggesting that participants are basing isometric lower limb forces on their sense of effort. These results for the lower limb are comparable to force matching tasks in the upper limbs of stroke participants[19,20] and in the lower limb of neurologically intact participants.[14]

Our study is the first to show that the sense of effort can also explain the magnitude of force generation during dynamic movements of the lower limbs in participants poststroke. Participants produced asymmetric lower limb forces even though the resistance was set low enough such that the paretic limb had the capacity to produce half of the force required. When participants were given no force instructions, normalizing lower limb forces to bilateral isokinetic MVC still revealed significant differences between limbs whereas the produce equal forces condition did not. During the no force instruction condition, participants most likely relied on their nonparetic limb more because they were used to their paretic limb being weaker and did not have any incentive to try to use that limb more. During the produce equal forces condition, however, we actively encouraged participants to try to use both lower limbs equally. When participants attempted to produce equal forces, their effort was divided between the 2 lower limbs equally and there were no significant differences between normalized forces. Therefore, for the produce equal forces condition, participants also relied more on their sense of effort, rather than proprioceptive feedback.

These results indicate that sense of effort is not only involved in static movements (ie, isometric force matching tasks) but also during movement. Although the task involved in experiment 2 was isotonic lower limb extensions, results likely can be extended to other movements that are functionally relevant for activities of daily living, such as standing up from a chair or climbing stairs. Indeed, a recent study examining

Figure 3
Experiment 2: Example Plots of Individual Foot Forces as a Function of Percentage of the Isotonic Cycle



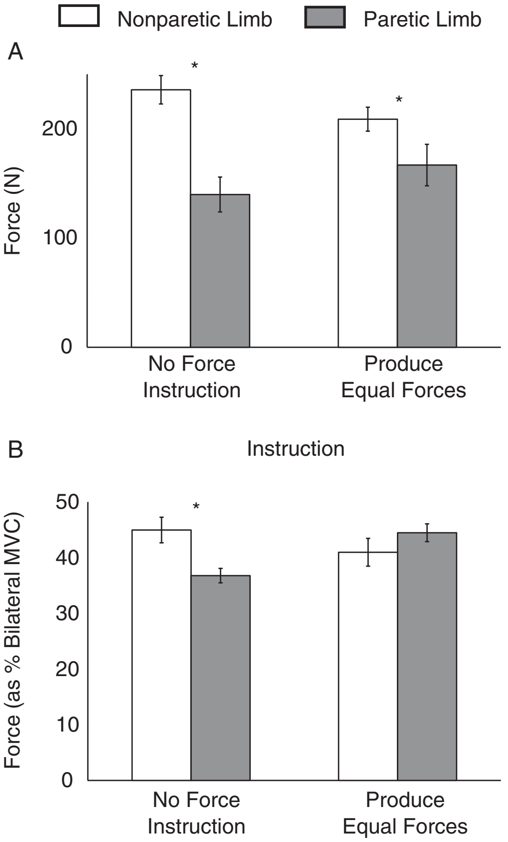
Note: From 0% to 50% is the extension phase of the cycle. Data shown are typical forces recorded for subjects 1, 2, 4, and 10. Subject 2 was the only participant that produced much higher absolute forces in the paretic limb than in the nonparetic limb during the produce equal forces condition. Black lines represent nonparetic limb forces and gray lines represent paretic limb forces. Dashed lines represent data from the no force instruction condition and solid lines represent data from the produce equal forces condition.

level of muscle activation during human walking by individuals with stroke has related findings. Milot et al[24] found that the level of electromyography (EMG) in lower limb muscles during walking were similar percentages of the isokinetic MVC electromyography value for the paretic and nonparetic limbs. This suggests that the magnitude of the efferent signal to each individual muscle was similarly scaled to the maximum force output of that muscle.[24] Considering both these previously published studies and our current results, it seems that the dominant factor in force production for static and dynamic movements in individuals with poststroke hemiparesis is sense of effort rather than proprioceptive feedback.

During normal motor behavior, however, there are a host of sensory signals that are integrated to influence muscle activation. The primary sensor signals derive from Golgi tendon organs, muscle spindles, and cutaneous receptors. Group 1b afferents within Golgi tendon organs are reliable sensors of local muscle tension. It was long believed that they only inhibited muscle activation as a protective mechanism, but they can monitor muscle tension over a wide range of force levels and can also provide autogenic excitation for positive force feedback.[25,26] Group 1a and 2 afferents within muscle spindles signal changes in muscle length and velocity. Studies show that even during static muscle contractions, as in experiment 1, muscle spindles provide the central nervous system with afferent feedback.[27] Cutaneous mechanoreceptors, specifically those that respond to mechanical pressure, can also affect motor commands during movement. We are not arguing that these sensory signals are unimportant and irrelevant. On the contrary, the kinesthesic information provided by these sensory receptors can be critical to movement dynamics.[27] Our conclusion is that, compared to afferent feedback, sense of effort dominates in the determination of efferent signal magnitude.

There have been many studies that have examined how altered sensory input affects the level of force production in humans. Chronically deafferented individuals have difficulty generating constant level forces for long durations.[17] If the individuals are distracted or devote less attention to the force generation task (eg, holding a cup of coffee), the forces decrease without concerted effort. However, they can grade their central commands to produce different force levels.[17,28] These observations are in line with our findings that sense of effort is the dominant factor determining force production. Acutely partially deafferented individuals can also judge forces accurately and have the ability to grade force production.[9,29] These results also support our conclusions.

Figure 4
Experiment 2: Average Forces During Isotonic Lower Limb Extension Trials



Note: The resistance level was set to 80% of the paretic limb peak force during the bilateral isokinetic maximum voluntary contraction (MVC) condition. White columns represent nonparetic limb forces and gray columns represent paretic limb forces. A, Absolute force shows significant difference between limbs for both the no force instruction and produce equal forces conditions (ANOVA, $^*P < .0001$ and $P = .0005$, respectively). B, Force normalized to bilateral isokinetic MVC shows a significant difference between limbs for the no force instruction condition (ANOVA, $^*P = .0002$) and no significant difference for the produce equal forces condition (ANOVA, $P = .2111$). Error bars are standard error of the mean.

There have been data and speculation that do not seem to directly support our results. Takarada et al[30] recently observed an overestimation of forces in neurologically intact participants undergoing a tourniquet-induced sensory alteration. It may be that the tourniquet methodology was not an ideal simulation of deafferentation without affecting efferent signals and/or muscle force capabilities. Sanes and Shadmehr[31] studied a position matching protocol in patients with chronic large fiber sensory neuropathy and concluded that peripheral afferents contribute partially to determining efferent signal magnitude. The difference in position matching protocol versus force matching protocol may be critical to interpreting Sanes and Shadmehr's results as it is known that motor control can be different during the 2 types of tasks.[32] It could be that in certain situations, the nervous system reweighs the importance of afferent sensory information verses sense of effort in the determination of the descending efferent signal.

Stroke patients in general have deficits in their sensory perception. It is typical for individuals to experience the loss of touch sensation and impaired proprioception.[33-35] It seems likely that these individuals would rely on all resources available to them to accurately control muscle activation. However, our findings that both isometric and isotonic force production are equal for both limbs when normalized to the bilateral maximum force generating capabilities of the limbs clearly points to feed-forward central command (sense of effort) as the dominant factor in force production.

Our participants did not seem to have updated their neural representation of their lower limb (ie, internal model) to account for their weakness even though they sustained this weakness anywhere from 7 to 39 months previously. Participants typically commented that using their paretic limb was harder, that it felt heavier, and that they did not have a good idea of how much force they were producing in the limb. Previous studies involving individuals with poststroke hemiparesis have also reported an increase in sensations of heaviness or effort when trying to move the paretic limb.[36,37] Figure 3 illustrates that participants do not understand the extent of their weakness. For example, compared to the no force instruction condition, when subject 1 was asked to produce equal forces in his lower limbs, he was able to generate more force in the paretic limb but not enough to match the force produced in his nonparetic limb. Subject 2 was more aware of the extent of his weakness and ended up overcompensating for his weakness by producing more force in his paretic limb than his nonparetic limb. His awareness was confirmed after the study in discussion with the experimenter. Without knowing the purpose of the experiment, he explained that he felt his paretic limb was so weak that he had to push even harder on that side to get what he believed to be an equivalent force output. Regardless of the strategy the participants used, they still had very poor ability to produce a given force with their paretic limb.

The results of the current study have some limitations because of the participant population and task. Although we only analyzed data on 9 participants, statistical analysis revealed clear significant differences as predicted by our hypotheses. We could not separate out the possibility of a false negative in either experiment, but post hoc analyses indicate that the magnitude of the differences, if there is one, is small. In relation to the experimental tasks, during both experiments only 1 force level was tested. Previous force matching studies have included 2 to 3 target force levels,[7,14,19] showing similar results for either all levels or the 2 highest target force levels. We chose to test participants in a simplified task of lower limb extensions that required no upper body stabilization. This allowed us to investigate force production in a controlled manner rather than using a more functional task, which would have made it harder to control for confounding factors. Finally, the current study did not include recording and analysis of electromyography. A previous lower limb force matching study that did record electromyography in neurologically intact participants did not have enough power to make strong conclusions relating muscle activity to lower limb forces.[14] Given the higher intersubject variability in EMG in poststroke participants it seems doubtful that EMG would have provided any new information.

Regardless of these limitations, it is apparent that weakness is not the only problem that stroke rehabilitation should focus on. This study shows that poststroke individuals also have an impaired awareness of their effort to force relationship that needs to be addressed. Physical therapists can use the information presented in this article relating to sense of effort and limb force asymmetry to design alternative training for these patients. For example, one new type of therapy could involve lower limb extensions with symmetry-based resistance.[22] With symmetry-based resistance, exercise resistance increases with increasing lower limb force asymmetry. This might provide patients with a means for recalibrating their effort to force relationship.[22] Regardless of the approach, stroke patients need to better understand how to use a stronger effort on their paretic side to compensate for their weakness.]

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