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Development of a Method to Quantify Inter-limb Coupling in Individuals with Hemiparetic Stroke*

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Abstract

A common motor deficit in individuals post-stroke is altered interlimb coupling. Efforts at one extremity can cause involuntary muscle activity and movement at a different extremity. An important step in understanding interlimb coupling and developing effective treatment strategies is to have an accurate quantification of the motor behavior. This paper outlines the development of an approach to measure interlimb coupling between the upper and lower extremity. Isometric and EMG based approaches were explored before determining that the use of a haptic robotic system was ideal to quantify altered interlimb coupling. This is a novel engineering approach that can measure biomechanical parameters while avoiding confounding factors. Preliminary evidence shows that lower extremity efforts cause involuntary movement in the upper extremity in stereotypical flexion and extension patterns.

I. Introduction

Of the 785,000 adults who survive a stroke each year, only 20% of individuals have regained normal use of their arm at three months post-stroke, and 26% of stroke survivors report significant impairments in ability to complete activities of daily living at six months post-stroke [1, 2]. One of the deficits seen following stroke is altered interlimb coordination. Altered interlimb coordination is expressed in the form of associated reactions, in which abnormal involuntary muscle activity in one limb occurs in response to voluntary activity in another limb. An example is that when an individual attempts to walk quickly to cross a street, their involved upper extremity may involuntarily move into a flexed posture.

Associated reactions can be elicited by high efforts and even involuntary activities including yawning, thus making them a significant clinical problem in that they interfere with activities of daily life, impede balance reactions, and have negative cosmetic effects [3–5].

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Unfortunately, clinical practice often treats the upper and lower extremities in isolation. Additionally, the use of high-intensity approaches in rehabilitation may actually be exacerbating these abnormal movements. For instance, gait training is often focused on maximizing neural drive using such approaches as fast walking, inclines, and resistance, all of which are likely to elicit associated reactions in the upper extremity. Such approaches may be reinforcing associated reactions in the upper extremity and promoting maladaptive neuroplasticity.

While abnormal coupling patterns have been extensively quantified within the upper [6–8] or lower extremity post-stroke [9, 10], abnormal coupling between limbs is poorly understood, in part due to difficulty in quantifying the behavior. Prior studies have relied on qualitative assessment [11], studied single joint torques [12–14], or used electromyography [15–17] as a measure of involuntary muscle activation. These approaches, as will be discussed in this paper, all have limitations and do not allow for a full characterization of interlimb coupling.

This paper will describe the development of a novel quantitative biomechanical approach to studying altered interlimb coupling. We will discuss the use of three approaches to quantifying associated reactions and their strengths and weaknesses. We ultimately found that a robotic approach which uses haptics to create a controlled environment is best for quantifying interlimb coupling. The haptic robotic approach avoided biases such as a rigid ground or variable limb weight, which were shown to be problematic in our first two approaches. We will provide preliminary evidence using this approach and discuss how this work can help in elucidating the neural factors underlying associated reactions. Having a robust tool for the quantification of interlimb coupling will allow for a better understanding of this motor deficit and pave the way for improved interventions.

II. Methods

The following details the evolution of our methodology to quantify abnormal interlimb coupling in individuals with chronic stroke including three different approaches. While our application is to measure the effect of lower limb efforts, specifically knee flexion and extension, on the upper extremity, the same methodology can be used with volitional efforts in the contralateral upper extremity. All individuals who participated in this research provided written consent. The experiment was approved by the Northwestern University Institutional Review Board.

A. Isometric Method

An isometric methodology was first employed to characterize the upper extremity torques elicited involuntarily during a lower extremity task. The methodology used to calculate upper extremity torques has been extensively used to study abnormal motor control within a limb (e.g. between shoulder and elbow [7, 18–20]), however, this was the first time the methodology has been applied to quantify interlimb coupling.

In this method, participants have their upper extremity rigidly coupled to a 6 degree of freedom load cell at the wrist. They are asked to perform maximal and submaximal (25, 40,

55, 70, and 85% of maximum) isometric knee flexion and extension torques while keeping their upper extremity at rest. Both the paretic and non-paretic lower extremities are tested. Feedback is only given on the voluntary knee torque direction, with no feedback given on the behavior of the upper extremity. Using Jacobian matrices and known joint configurations of the upper extremity, forces and moments measured by the load cell are converted to joint torques at the elbow and shoulder. Joint torques are filtered with a 250 ms moving average filter. For each lower extremity task, we calculated the maximum upper extremity torque generated and normalized it to the maximum torque the participant can voluntarily generate in that direction.

B. Electromyography Method

In this method, surface EMG electrodes (Delsys, Boston, MA) were placed on participants' shoulder, elbow, and wrist muscles as well as quadriceps and hamstrings. Participants were instructed to have their upper extremities resting in their laps while performing maximal and submaximal isometric knee flexion and extension torques, as done in the isometric method. Feedback was only given on the lower extremity torque. Participants also performed maximal contractions against manual resistance in the primary direction of each instrumented muscle in order to normalize EMG activity. All EMG was baseline corrected, rectified, and low pass filtered. Peak EMG amplitude for each lower extremity task was normalized to the maximum EMG amplitude for that muscle.

C. Haptic Robotic Method

Based on the findings employing the first two methods (see Results and Discussion sections), we developed the following measurement criteria:

1. avoid a rigid biomechanical ground for the upper extremity
2. measure joint torques and kinematics
3. be sensitive to wide range of presentations of interlimb coupling
4. compensate for the weight of the limb

These criteria led us to the use of the Arm Coordination Training or ACT-3D haptic robot, shown in Fig. 1. The ACT-3D consists of the admittance controlled HapticMaster robot (Moog-FCS V.C., The Netherlands) with a six degree of freedom load cell end effector (JR3, Woodland, CA) placed on a Biodex t-base system with an experimental Biodex chair. It is capable of rendering haptic environments as well as recording joint torques and kinematics. Participants are coupled to the end effector with a rigid forearm-hand orthosis. Haptic effects are utilized in two ways. First, a bias force is used in the z-direction to compensate for the weight of the limb. Second, multidirectional haptic springs are used to provide support for the limb without creating a rigid ground. The springs support the participant in a resting position (85 degrees shoulder abduction, 40 degrees horizontal adduction, 90 degrees elbow flexion) so that the participant does not need to exert any effort, which may influence the behavior during the task. However, unlike the rigid isometric setup, the haptic springs are not so stiff that they can be used as a rigid ground to gain mechanical advantage. Participants may move in any direction, and the springs can be conceptualized as a spring connecting the end effector to the starting rest position, thus always exerting a force in the direction of the

starting position. Through Hooke's law, the force applied by the participant will dictate the displacement of their limb. Preliminary studies showed that a spring constant of $k = 200 \text{ Nm}$ provided sufficient stiffness to keep the participant in the resting position without voluntary effort, but did not prevent movement in any direction.

In using this method, the same general protocol is applied, in which participants perform maximal and submaximal knee flexion and extension torques while their upper extremity is coupled to the ACT-3D robot. As before, they are instructed to relax their arm. The device measures upper extremity kinematics as well as forces and moments, which can be converted to elbow and shoulder torques as done in the isometric protocol.

III. Results

A. Isometric Method Results

Fig. 2 shows example torque traces for a healthy control participant during a knee flexion task. As this figure shows, upper extremity torques reached greater than 40% of maximum torques during a lower extremity task. This is due to the isometric setup introducing a rigid ground that can give participants a biomechanical advantage when eliciting torques in the lower extremity. Hence, by the nature of the method, the behavior we wish to quantify is being altered.

B. Electromyography Method Results

Fig. 3 demonstrates typical responses in the upper extremity, for paretic knee extension in Fig. 3a and non-paretic knee flexion in Fig. 3b. In Fig 3a, upper and lower extremities extend involuntarily. In Fig 3b, both the upper and lower extremity move into stereotypical flexion synergy patterns. However, this pattern is not apparent from EMG results. EMG patterns were found to frequently differ from what was visually observed, for instance, triceps would demonstrate the greatest normalized activity, while the participant was observed flexing at the elbow. This is due to difficulty in eliciting voluntary maximum contractions post-stroke. EMGs were also highly inconsistent between trials. Additionally, the observed amplitude of movements was highly variable, with some participants demonstrating large joint excursions similar to what is seen in Fig 3, while others had only slight limb movements. The amplitude of the movements may be biased by the weight of the limb. A heavier limb requires larger amounts of muscle activation to create an observable movement. For this reason, an additional design criteria was added that the methodology must account for the weight of the upper extremity.

C. Haptic Robotic Method Results

Fig. 4 demonstrates the upper extremity kinematics in an individual with chronic stroke using the haptic robotic methodology. As shown, knee flexion (Fig. 4a) was coupled with elbow flexion and shoulder abduction, while knee extension (Fig. 4b) was coupled with elbow extension and shoulder adduction.

IV. Discussion

A. Comparison of Methodologies

This paper outlined three different methods for measuring associated reactions and showed results for each of them. The first two methods showed notable limitations. While the isometric methodology allows for a biomechanical quantification of joint torques, the nature of the setup alters the motor behavior. The rigid device for the upper extremity provides a mechanical advantage for the participant when performing lower extremity tasks. By “bracing” themselves with the isometric device, the behavior of interlimb coupling is altered, even in healthy control participants. This does not allow us to determine the true expression of interlimb coupling post-stroke. Additionally, this methodology does not allow an upper extremity dual task in the future. Dual tasks are important to differentiate between what may happen spontaneously and what movement participant is actually constrained to. However, with this isometric approach there is no movement of the upper extremity to provide participants with intuitive feedback. Providing additional visual feedback on upper extremity torques can be confusing and require greater cognitive and attention skills, as participants are already receiving feedback on lower extremity torques.

Using EMG analysis, we were able to avoid the problem of the rigid coupling, however, several drawbacks were apparent. First, use of EMG does not give as complete a picture of the motor behavior as with kinetic measures such as joint torques. EMG is much more variable, and dependent on normalization processes that may be skewed in individuals with stroke due to their impairments with volitionally activation of paretic muscles. While motion capture could be used to compliment the EMG analysis, qualitative observations suggest that the degree of limb movement may be strongly influenced by limb weight, which introduces a confounding factor.

The use of a haptic system is able to successfully address the limitations of the first two approaches. Haptic springs are able to provide support for the limb so that participants can keep their upper extremity relaxed, without being coupled to a rigid ground. The system can capture kinetics and kinematics, and the weight of the limb can be compensated for. Lastly, since the upper extremity is able to move and is within the visual field of the participant, dual tasks can be implemented in the future, such that participants can be asked to minimize motion in their upper paretic extremity. Additionally, the same ACT-3D device can be used while the subject is performing an upper extremity reaching movement, which allows for the determination of how lower extremity activity may impair reaching ability. This is an important next step in understanding the constraints imposed by altered interlimb coupling.

B. Interpretation of Underlying Neural Mechanisms

A careful quantification of associated reactions can lead to understanding the underlying neural mechanisms. While further research is necessary, the preliminary results demonstrate that lower extremity efforts result in upper extremity movement patterns consistent with flexion and extension synergy patterns. This is in agreement with past qualitative work and clinical observations. Flexion and extension synergy patterns have been previously studied extensively in the upper limb of individuals with hemiparesis, and attributed to an

upregulation of brainstem pathways. Cortical and subcortical lesions disrupt the descending corticospinal motor pathways, which are high-resolution motor pathways that allow for finely tuned movements that can be isolated to a single joint. Damage to corticospinal tracts following stroke results in an increased reliance on brainstem motor pathways, including the reticulospinal and vestibulospinal tracts. Unlike the corticospinal tracts, brainstem pathways branch significantly at the level of the cord, causing a loss in independent joint control. The flexion synergy is a manifestation of this, in which shoulder abduction is coupled with elbow, wrist, and finger flexion, limiting an individual's ability to perform functional reaching movements [21] and opening the hand [22]. While the flexion synergy has been quantified extensively within the upper extremity, our novel methodology introduced in this paper allows for the first quantitative biomechanics study of synergy patterns elicited between limbs.

V. Conclusion

This paper provides a description of the development of a novel methodology to quantify altered interlimb coupling in individuals with hemiparesis. Using a haptic robotic system, we can provide a biomechanical (i.e., kinetic and kinematic) characterization of involuntary upper extremity activity that is elicited by lower extremity tasks. An improved understanding of interlimb coupling post-stroke can help shift the clinical paradigm of treating upper and lower extremities in isolation, and lead to the development of specific interventions that target the abnormal interlimb coupling.

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Figure 1.
Participant positioned in ACT-3D Device

Figure 2.
Isometric upper extremity torques in healthy control participant during knee flexion.

Figure 3.
Examples of interlimb coupling patterns. a) Child with prenatal stroke demonstrates extension in all limbs; b) Adult stroke participant demonstrates flexion pattern in paretic upper and lower extremity in response to non-paretic knee flexion.

Figure 4.

a. Elbow flexion and shoulder abduction elicited by knee flexion.

b. Elbow extension and shoulder adduction due to knee extension.