Simulations of hamstring lengthening surgery in crouch gait cerebral palsy

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1 Introduction

Crouch gait is one of the common gait deviations observed in cerebral palsy (CP) patients and is due to spasticity or contracture affecting the hamstring muscle [1]. This gait abnormality is often treated by hamstring lengthening surgery, consisting of cuts applied to the hamstring's aponeurosis leading to an increased resting length of connective tissue and muscle weakness [2]. However, this treatment's effectiveness depends on the proper capability to distinguish if the hamstring's hyper-resistance to stretch is due to muscle contractures or muscle spasticity [1, 3]. Excessive resistance of muscle contractures is due to overstretched conditions of sarcomere lengths [4]. In addition, contractures present increased collagen leading to higher passive responses [4]. On the other hand, spasticity is defined as velocity-dependent hyperexcitability to the stretch reflex and reduction of presynaptic and reciprocal inhibition [5].
Neuromuscular simulations can be powerful tools for modeling and isolating different kinds of impairments in a virtual environment. Previous neuromuscular models studied pathological behaviors in human locomotion. Muscle contractures have been modeled either by altering the passive muscle properties [6] or the muscle optimal fiber length [7, 8], whereas neural spasticity has been modeled by modifying the linear gain of the length, velocity, acceleration, or force-dependent feedback and by altering the reciprocal inhibition pathways among agonist and antagonist muscles [6, 9-10].
Previous computer simulation studies have also investigated the effects of surgeries modeling tendon transfer and osteotomies [11, 12]. Furthermore, Pitto et al. developed the SimCP framework simulating the effect of different surgeries on gait performance, enabling virtual surgery on the models [13]. In this study, we aim to evaluate the effect hamstring lengthening in alleviating crouch gait deviations associated with the isolated impact of hamstring's spasticity, contracture, and the combination of these two impairments. We use the Gait Profile Score (GPS) to evaluate the number of deviations for the different simulations [14].

2 Methods

We used the SCONE software simulation framework to generate gait simulations [15]. We used the musculoskeletal model from Ong et al. constrained in the sagittal plane with a total of nine degrees of freedom (DoFs) and nine Hill-type muscles, including the hamstring.
The spinal controller used to replicate muscle hypertonia is the same one we proposed in our previous study, and it is composed of a CPGs controller and a reflex controller accounting for sensory feedback from Ia, II, Ib fibers, Renshaw cells and reciprocal inhibition mechanisms between agonist and antagonist muscles [16].
We modeled the effects of biomechanical contractures by decreasing the value of the optimal fiber length (l_{opt}) and the parameter associated with the amount of muscle strain necessary to produce a maximum force equal to the muscle's maximum isometric force (ε_0). We apply the same scaling factor to l_{opt} and ε_0 from 1.0 (healthy behavior: TD) to 0.6 to study the effect of the decreasing values of these parameters.
To model muscle hypertonia, we alter the spinal connections of the reflex controller by disabling (synaptic weight equal to 0) the inhibitory connections from Ib fibers and the reciprocal inhibition with antagonist muscles and increasing the synaptic weights of connections from the Ia sensory neuron. We explore the increasing values of Ia weights from 1.0 to 5.0.
Finally, hamstring lengthening surgery is modeled by decreasing the slack length (l_{slack}) of the element in series with the contractile element, and by decreasing the muscle's maximum isometric force (F_{max}) to model muscle weakness. We apply a scaling factor to l_{slack} from 1.0 to 1.15 and another scaling factor to F_{max} from 1.0 to 0.85. To identify the amount of gait deviation compared to the healthy solution (TD), we assign to each solution a Gait Profile Score (GPS) [14]. The different solutions are obtained by optimizing the controller parameters for each combination of impairments, as described in our previous study [16].

3 Results

Figure 1 shows the GPS for different combinations of neural spasticity and biomechanical contractures without surgery, and with mild, moderate, and severe surgeries.
We can observe that the GPS increases with the increasing severity of contractures and spasticity. The largest deviations are observed for solutions including contr 60%. When a mild surgery is applied, we can observe consistently decreased GPS values for contr 80% and contr 70% in the absence of spasticity and with Ia input = 1.0. For severe impairments, there are still consistent gait deviations. With moderate surgery levels, decreasing GPS values can be observed for

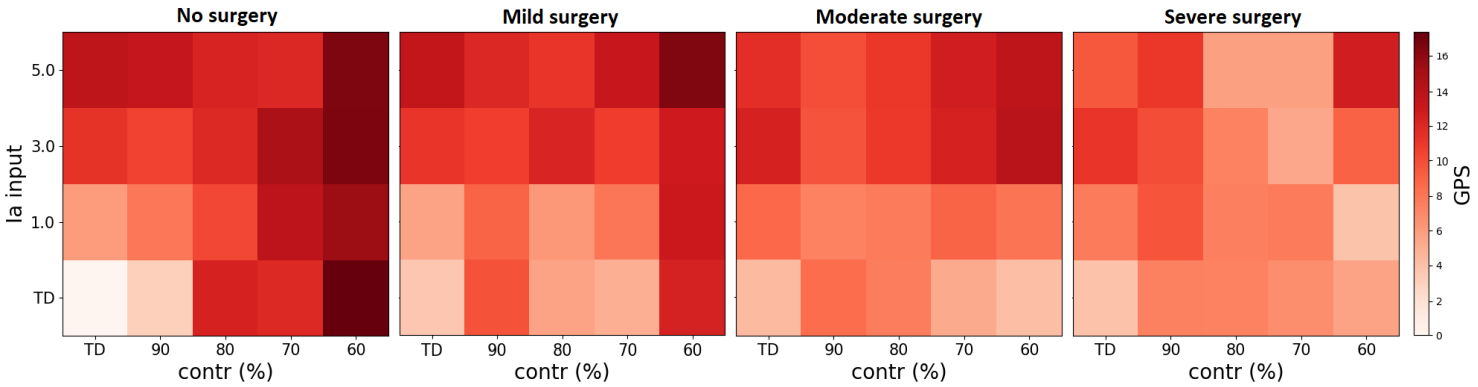

Figure 1: Gait Profile Score (GPS) for different combinations of hamstring spasticity and contractures without surgery, and with mild, moderate and severe surgeries.

severe contracture levels (contr 60 %) without spasticity or with Ia input = 1.0. There are decreasing GPS levels for severe surgery for the combinations including Ia input = 3.0, 5.0, and contr 80%, 70%.

4 Discussion

In this study, we reproduced the effect of hamstring lengthening surgeries with different combinations of hamstring spasticity and contractures. Compared to past studies, we considered both passive stiffness and reduced optimal fiber length to model muscle contractures and decreased the level of abstraction for modeling spasticity. We observed that, without surgeries, the crouch gait behavior could be generated for any combination in which contr = 0.8 or higher and Ia input = 3.0 or higher. In general, neural and biomechanical impairments generate similar gait deviations, with slightly more severe deviations observed for extreme contractures. Despite the similar effects of the two impairments on gait deviations, the hyper-resistance force reacting to stretch is mainly generated by the high stiffness of passive components in isolated muscle contracture. In contrast, this hyper-resistance is due to active forces generated by muscle overactivity in spasticity.

Hamstring lengthening seems to be particularly effective in reducing gait deviations due to isolated muscle contractures or with a low level of spasticity. Severe surgeries may improve crouch gait conditions for selective combinations of contractures and severe spasticity, also reproducing behaviors similar to TD. In general, hamstring lengthening alleviates crouch gait conditions and drastically decreases passive forces. Crouch gaits affected by muscle contractures benefit from the reduced passive forces that are the main causes of gait deviations, whereas crouch gaits affected by spasticity may benefit from the weakness induced by the treatment. However, simulations show that hamstring lengthening seldom significantly benefits conditions with high spastic levels.

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