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Executive Summary of the Thesis

Rehabilitation on the rowing machine for children with unilateral spastic cerebral palsy: characterization of the kinamatic variables and of the muscle lengths

Laurea Magistrale in Biomedical Engineering - Ingegneria Biomedica

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1. Introduction

Cerebral Palsy (CP) is a prevalent childhood-onset disorder that affects the central and peripheral nervous system, leading to permanent movement and posture impairments [1],[2]. It is considered the most common cause of childhood disability. CP is characterized by non-progressive disturbances in the developing fetal or infant brain, resulting in limitations in activities and motor function. In addition to motor disorders, individuals with CP may experience challenges in sensation, perception, cognition, communication, behavior and they may be prone to epilepsy and secondary musculoskeletal problems [3].
The neuropathology of CP is primarily characterized by deficits in posture and motor function, leading to abnormalities in muscle coordination and control. These deficits are attributed to a "permanent disorder" caused by immature brain injury during fetal development or early childhood. However, clinical outcomes can be improved through surgical interventions, drug therapies and rehabilitative interventions.
This study presents an innovative rehabilitation program designed for children with unilateral spastic CP, which is intended to be used in conjunction with conventional physiotherapies. In CP, the musculoskeletal system is particularly affected, resulting in shorter and smaller muscles with reduced fiber diameter. Sarcomeres, the basic unit of muscle contraction, are also elongated [2]. In spastic CP, abnormal muscle tone hypertrophy can be observed, primarily affecting the flexors of the upper limbs and extensors of the lower limbs. When only one side of the body is affected, the condition is referred to as "unilateral"[4]. The non-physiological muscle parameters limit the active force and the joint range of motion in the affected limb, hindering everyday activities. Furthermore, sensory deprivation occurs as the child increasingly relies on the healthy limb, further reducing mobility in the affected one.
Rowing machine training is proposed as a means to prevent the deterioration of neural pathways by encouraging the use of both limbs and modifying non-physiological muscle parameters. The effects of this therapy are assessed through two functional tests: reaching and hand-to-mouth tasks, which are commonly used to quantify up-

per limb functional limitations in daily life activities [5],[6]. During the execution of these tests, key kinematic variables and muscle-tendon length are computed.
In summary, this study presents a novel rehabilitation program for children with unilateral spastic CP, aiming to improve motor function and daily life activities. The program incorporates rowing machine training alongside conventional physiotherapies. The effects of the therapy are evaluated through functional tests, providing valuable insights into the potential benefits of this intervention.

2. Material and methods

2.1. Partecipants

The proposed trial has received the approval from the Ethics Committee of the I.R.C.C.S. Eugenio Medea - Associazione La Nostra Famiglia. Informed consent has been obtained from all parents and guardians. The study involves three patients with CP (3 M, age: 10 ± 3 years; height: 1.42 ± 0.2 m; weight: 32.7 ± 6.0 kg) recruited in collaboration with the I.R.C.C.S. Eugenio Medea - Associazione La Nostra Famiglia (Bosisio Parini, Lecco) and ten healthy children (8 M 2 F, age: 10 ± 2 years; height: 1.41 ± 0.1 m; weight: 32.0 ± 8.6 kg). The main inclusion criteria for the study are as follows: patients diagnosed with Unilateral Spastic Cerebral Palsy (USCP), aged between seven and twelve years, classified with a level 1-2 of the Gross Motor Function Classification System, and not requiring orthosis or walking assistance.

2.2. Instrumentation

The primary tools used in the study include:

- Rowing machine: a Concept 2 ergometer, typically used to simulate the rowing gesture. The specific model used is the Concept2, Inc., Model D RowErg, provided by Società Canottieri Lecco.
- MVN Awinda Xsens used for 3D kinematic analysis. It consists of 17 wireless inertial measurement units accurately placed on body segments using elastic bands. The MVN Analyze software facilitates calibration, data recording and visualization.
- Opensim software: an open-source, user-extensible software used for developing musculoskeletal models and dynamic motion simulation [7]. The study utilizes several tools within Opensim, including the Scale tool, IMU Placer, IMU Inverse Kinematics and Analyze tool.

2.3. Experimental Procedure

Data acquisition tooks place at the Società Canottieri Lecco once a week, comprising a total of five sessions for the experimental group (three patients) and a single session for the control group. The experimental protocol involved an initial warm-up to familiarize participants with the rowing motion. Subsequently, two upper limb functional assessments were conducted: the reaching and hand-to-mouth tests. Both limbs performed twelve repetitions. Following the assessments, the training on the rowing machine was carried out, consisting of fifteen rowing stroke cycles.

2.4. Data analysis

For analysis, eight repetitions were selected for the reaching test, five for the hand to mouth motion and eight for the full-body rowing exercise. The files obtained from MVN Analyze were imported into Opensim for model scaling, kinematic analysis and muscle-tendon length estimation.
MATLAB®was employed to split the repetitions and identify the different phases of the gesture (going, adjusting, returning). Partitions was performed by selecting those points where the velocity overcame a certain threshold. To assess the functional limitation of the affected limb, a *two-tailed paired t-test* was conducted using MATLAB ($\alpha = 0.05$), after checking the normality of the data using the "*normalitytest*" function [8]. This analysis compared the performance between the affected and non-affected side, as well as pre and post-rehabilitation. Cohen's d coefficient was calculated to quantify the effect of the rehabilitation. Furthermore, a Statistical Parametric Mapping (SPM) analysis was executed to highlight statistically significant differences in joint angles and muscle-tendon lengths during the cycles between the patient's affected and less affected limbs ($\alpha = 0.05$).

3. Results and discussion

To evaluate the functionality of the upper limbs during the functional tests, the study examined the main temporal parameters mentioned in the literature [5],[6],[9]. By comparing the temporal parameters of the affected and unaffected limbs, significant differences in task performance were identified. Both the reaching and the hand-to-mouth tasks resulted more difficult with the affected limb, as it exhibited slower movements. In the first session, significant differences were observed in all the parameters considered, particularly in the reaching test, where the adjustment ($p\_value < 0.05$) and return ($p\_value < 0.05$) phases appeared more prolonged.
Following rehabilitation, the time required for the adjustment phase was significantly reduced, and no significant difference remained between the two limbs. Figure 1 displayed the flexion-extension angle of the elbow during the reaching test, highlighting the limited joint excursion of the affected limb compared to the unaffected limb (50 degrees for the unaffected limb vs. 35 degrees for the affected limb). The gray areas indicate the phase of the cycle (24-75%) where significant performance differences were observed between the affected (red) and unaffected limbs (green), corresponding to the maximum extension of the limb.

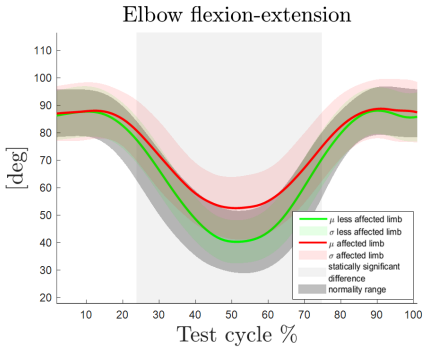

Figure 1: Mean and standard deviation with the SPM{t} statistics of the elbow flexion-extension angle of three patients with USCP during the reaching test for the affected side (red) and the less affected side (green). In grey the normality band.

The limitation of upper limb extension was compared to muscle-tendon length during the task. The flexor muscles, including the biceps brachii, the brachialis and the brachioradialis, were shorter in the affected limb, while the extensors (brachialis triceps and anconeus) were more elongated.
In the hand-to-mouth functional test, significant differences in all temporal parameters were detected between the affected and unaffected limbs both pre and post-rehabilitation. The difference seemed to decrease during the returning phase. It is important to note that the reduced difference was not due to a faster execution with the affected limb but rather to a slower returning phase of the unaffected limb (indicated by a large effect size of the unaffected limb). Nonetheless, after rehabilitation, the time required to perform this phase was significantly reduced compared to the pre-rehabilitation value ($p\_value < 0.05$, d = 0.47). The training also led to a decrease in the total time required to complete the task ($p\_value < 0.05$, d = 0.46).
Figure 2 depicts the flexion-extension angle of the elbow during the hand-to-mouth test, revealing the limited joint extension of the affected limb. The gray areas in the background illustrate the restriction in extension at the beginning and at the end of the task, as evidenced by the shortening of the flexor muscles [2].

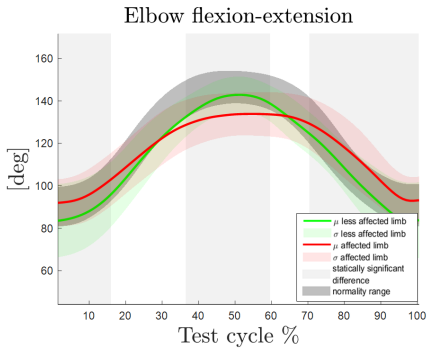

Figure 2: Mean and standard deviation with the SPMt statistics of the elbow flexion-extension angle of three patients with USCP during the hand-to-mouth test for the affected side (red) and less affected side (green). In grey the normality band.

During the hand-to-mouth test, the extensors of the joint, such as the triceps and the anconeus, were more elongated in the affected limb while the flexors were more shortened in the initial and final phases of the task.
The analysis of muscle length in the two func-

tional tests for the upper limbs demonstrated greater shortening of the flexors in the affected arm due to their hypertonicity. The flexors and extensors of the affected limb did not exhibit the same excursion (in terms of length) as those in the unaffected limb, resulting in limited joint excursion, as shown in Figures 1, 2.

The elbow joint showed increased flexion at the beginning and end of the cycle (Fig. 3). The brachialis and brachioradialis muscles appeared more shortened, while the anconeus and triceps muscles (especially the medial and lateral) exhibited greater elongation

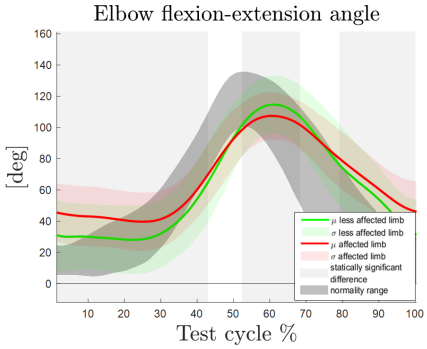

Figure 3: Mean and standard deviation with the SPMt statistics of the elbow flexion-extension angle of three patients with USCP during the rowing for the affected side (red) and less affected side (green). In grey the normality band.

The knee joint exhibited a significant difference between the two limbs, with the affected limb showing greater extension (Fig. 4). The extensors, particularly the vastus muscles (intermediate, lateral, medial) were shortened, while the flexors, particularly the short head of the biceps femoris, appeared elongate.

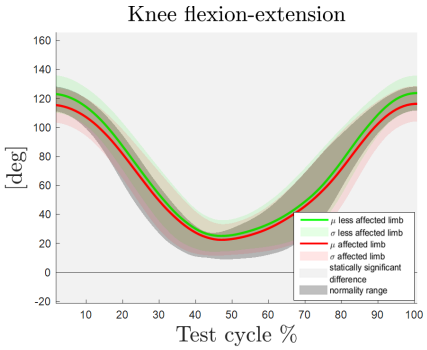

Figure 4: Mean and standard deviation with the SPMt statistics of the knee flexion-extension angle of three patients with USCP during the reaching test for the affected side (red) and less affected side (green). In grey the normality band.

Finally, the ankle joint was examined and it was found that the affected limb showed increased plantar flexion at the beginning and at the end of the cycle (Fig. 5). The soleus muscle, responsible for plantar flexion, appeared more shortened, while the tibialis anterior muscle, responsible for dorsiflexion, showed greater elongation.

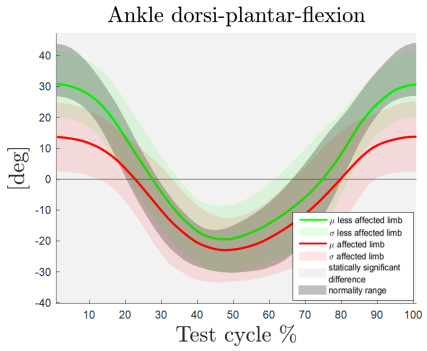

Figure 5: Mean and standard deviation with the SPMt statistics of the ankle dorsi-plantar-flexion angle of three patients with USCP during the reaching test for the affected side (red) and less affected side (green). In grey the normality band.

The analysis of kinematic variables and the variation in muscle-tendon length during the rowing exercise confirmed the shortening of lower limb extensors and upper limb flexors due to hypertonicity. However, the behavior of biarticular muscles such as the rectus femoris, biceps femoris, semimembranosus, semitendinosus and gastrocnemius was not fully understood. A pre and post-rehabilitation analysis was not con-

ducted in the study, preventing an assessment of whether the training resulted in muscle lengthening. A limitation of the study pertains to the control group chosen for the analysis. To evaluate the effectiveness of rehabilitation, a group of children with unilateral spastic CP could undergo only the tests without training. Furthermore, to enhance statistical significance, a larger number of patients should undergo the training.

4. Conclusions and future work

The study presented proposes an innovative approach to physiotherapy that can be combined with traditional rehabilitation for children with unilateral spastic cerebral palsy. In unilateral spastic CP, only one side of the body is affected by the condition, resulting in significant functional impairments. Simple daily activities like grasping an object or bringing it to the mouth can be challenging when using the affected limb. The limited number of sarcomeres in the affected muscles restricts joint movement and reduces force production. As a result, children tend to rely heavily on the unaffected limb, further diminishing the mobility of the affected limb due to neural pathway degradation.

To counteract this phenomenon and directly address muscle-level parameters such as muscle length, the study proposes training on a rowing machine. Previous research by *Blazevich et al.* has shown that involving a muscle in its entirety can lead to physiological lengthening [10]. The training protocol involves performing fifteen rowing stroke cycles, specifically targeting the joints and muscles most affected by the disease. Kinematic variables were captured using Awinda Xsens sensors, while Opensim software was utilized to estimate changes in muscle length.

To evaluate the effects of rehabilitation, the child underwent two functional assessments for the upper limbs: the reaching test and the hand-to-mouth test. These exercises represent common yet sufficiently complex gestures to study the limitations faced by children with hemiplegia. Analysis of the main temporal parameters revealed significant differences between performing the tests with the affected and unaffected limbs. Movements were slower with the affected limb, and the speed profile was not smooth. Following the five training sessions, while differences persisted, there was a significant reduction in the time required to perform the adjustment phase (reaching) and return phase (hand-to-mouth) – the two most challenging phases for children with CP [6]. Future investigations could include the study of additional parameters such as movement precision and presence of tremors, which were not addressed in this study. The analysis of joint excursion highlighted limitations in the range of motion, such as reduced extension during reaching and increased flexion in the initial and final phases of hand-to-mouth motion. The reduced range of motion can be attributed to the shortened muscle fibers, as demonstrated by the graphs obtained from SPM analysis. Specifically, in the upper limbs the flexors (biceps brachii, brachialis, brachioradialis) were more shortened and activated while the extensors (triceps and anconeus) were elongated and weaker due to hypertonicity of the flexors. On the contrary, in the lower limbs, the extensors are the ones affected by hypertonicity. Future developments could include the quantification of muscle-tendon length variations obtained after the training.

In conclusion, despite some differences in test performance have emerged even after rehabilitation, training on the rowing ergometer reduced the time required to perform the two most critical phases of the functional tests: the adjustment and returning phase. Therefore, training on the rowing ergometer represents an innovative and engaging method for children with CP that can be combined with standard rehabilitation. Training conducted with greater continuity and a higher number of sessions could lead to greater symmetry in task performance. Additionally, assessing muscle length during functional tests and motor tasks can be a highly effective tool for evaluating limb functionality.

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