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Analysis of biomechanical data to determine the degree of users participation during robotic-assisted gait rehabilitation*

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Abstract— **Recent studies have shown evidence indicating that effective robotic rehabilitation is only possible when the user actively participates during training. Providing a complete effective biofeedback to the patient representing his compliance to the therapy and his performance is thought that his active participation will be enhanced significantly, thus, improving his rehabilitation. We have performed a study with the driven gait orthosis (DGO) Lokomat (Hocoma AG, Volketswil, Switzerland). The objective of the present study is the analysis of the effect of different types of participation (attention to the functional task) from subjects receiving robotic assisted gait training on the kinematic and kinetic patterns. The obtained results provide useful evidence of specific biomechanical features that can be used to design more useful, robust, focused and intuitive biomechanical biofeedback during robotic assisted gait rehabilitation in stroke survivors.**

I. INTRODUCTION

Robotic-assisted gait rehabilitation has been studied as an alternative [1], [2] to the traditional rehabilitation methods during last years, showing several advantages compared to manual treadmill training, as continuous support for the legs, high repetition accuracy, and prolonged training duration. A disadvantage is the lack of physical contact between the therapist and the patient, often used by the therapist to "feel" the patient's ability and activity. With this information, the therapist can provide feedback to the patient, give training instructions and help to improve the patient's motivation.

Recent studies have shown evidence indicating that robotic-assisted rehabilitation can be improved providing to the patient artificial feedback about his performance during training [3]-[5]. This is becoming requirement in robotic-assisted neurorehabilitation since humans that suffer from neurological disorders have difficulties in reception and interpretation of proprioceptive feedback. Feedback is also important for motivation. Providing frequent information to the patients about their progress is a proved method to increase their voluntary effort during training [6], improving their compliance and endurance.

There are several commercial and noncommercial systems to conduct robotic gait rehabilitation for patients with neurological disorders [11]-[13]. One of these devices is Lokomat. Briefly, Lokomat is a driven bilateral lower extremity orthosis or exoskeleton that automates locomotion moving the lower limbs of the user through predefined trajectories using current and position controllers, with motor drives at the hip and knee joints; ankle-foot movement is inducted by passive foot lifters. It combines the exoskeleton itself with a treadmill and a body weight support system [11].

In this work we present a study with Lokomat, to investigate the degree of user's participation while performing training exercises assisted by the robot. The main goal is to determine the effects of variation of user's degree of participation in the biomechanics of gait, in order to assess its usability as feedback for the patient, as well as for the therapist. Other authors have studied the effect of the user's performance in the variation of the biomechanical patterns [7]-[9].

II. METHODS

A. Participants

Participants were a set of eight volunteers (1 female, 7 male), aged between 20 and 35 years, heights between 1,62 and 1,88 meters. All participants gave informed consent. None of the subjects reported any type of cognitive damage or orthopedic impairment. None of the subjects received training with the robot before.

B. Experimental conditions

Experiments were performed at the facilities of the Bioengineering Group, at Spanish National Research Council. During data collection, participants were fitted to Lokomat.

In order to evaluate different types of participation during robotic-guided gait training, we instructed the subjects to perform in a) *active*, b) *passive* and c) *distracted* conditions. In the *active* condition the subject was instructed to actively work with the robot, matching the movement robot imposed at the hip and ankle joints. In the *passive* condition the subject was instructed to avoid voluntary leg muscle's activation, letting the exoskeleton to drive the joints movement and only contributing to stabilization during the stance phase. During the *distracted* condition, the subjects were instructed to be walk actively and simultaneously perform mentally an arithmetic operation that consisted in counting backwards and subtraction starting from a random number that was displayed in steps of 7.

The percentage of assistance used by the exoskeleton to drive the joints is controlled with a parameter named Guidance Force, which range goes from 0% to 100%. A high Guidance Force implies that the robot exert higher

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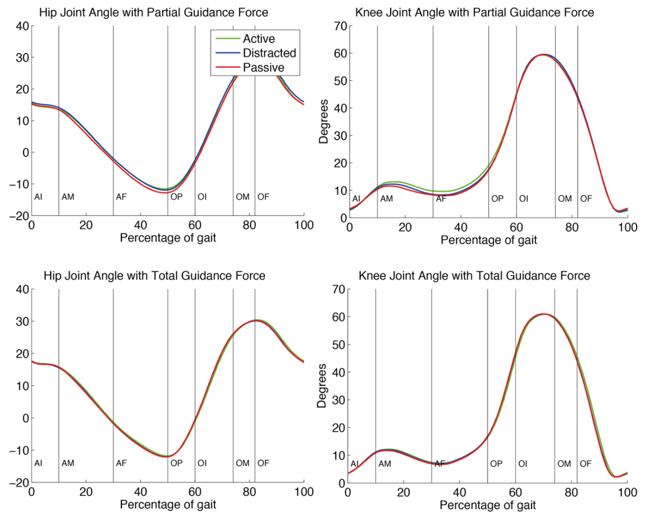

Fig. 1. Joint angles of one subject. From left to right columns: Hip and knee joint angles. From top to bottom rows: Partial and Total Guidance Forces.

efforts moving them, e.g. with a value of 100% the robot will do all the work moving the limbs, whereas a value of 20% implies that the robot is mostly passive, and couldn't be strong enough to move the patient's limbs. To see the effect of this parameter on the performance of the subject, two different values were defined to perform the exercises: a Total Guidance Force, with a value of 100% effort by the robot, and a Partial Guidance Force, which was customized for every volunteer with a value comprised between 20% to 40%. This force was the minimum needed by the robot to move the patient's limb when he was acting passively without hindering the movement.

The body weight support (BWS) was customized for each patient, selecting the minimum necessary to keep the volunteer in a comfortable upright posture during walk. The speed of the treadmill was also customized for each volunteer, given the length of his leg [6].

The volunteers were asked to walk under 6 combinations of the 3 conditions with the 2 levels of Guidance Force: Total Guidance Force with *active* (AT), *passive* (PT) and *distracted* (DT) conditions, and Partial Guidance Force with *active* (AP), *passive* (PP), and *distracted* (DP) conditions, having 2 minutes of duration per each combination of condition and guidance force (from now, *trial*). Each *trial* was alternated randomly and repeated 3 times. The body weight support and the speed of the treadmill were changed between participants, but kept constant during all their respective *trials*.

Other adjustable parameters concerning the setup of the patient, as the angular range of motion of both hip and knee, or the offset angle in which their trajectories can be affected were customized for each patient, adjusting them until they felt comfortable, in order to establish a gait pattern as close as their own natural pattern.

C. Data acquisition and analysis

Data collection was performed using Simulink (MathWorks) and a data acquisition (DAQ) board conected to the outputs of the Lokomat's internal sensors; analysis was performed using MatLab (MathWorks). Kinetic and kinematic data recorded from joints of dominant leg consisted in joint angles of hip (HR) and knee (KR), and joint forces at hip (HF) and knee (KF). For each participant, 3 sets of data were collected per each *trial*, representing in total 18 minutes of walking per participant. For analysis, the 3 sets of data corresponding to each *trial* were concatenated to create a unique set of data per *trial*, and then, splitted into single gait cycles, which were normalized in number of samples. Finally, for each set of data corresponding to each *trial*, averages values between cycles were obtained, creating a gait profile per *trial* for each subject (Fig. 1 and 2). These gait profiles represent the average gait performance of the subject under determined condition and guidance force.

Gait profile of each *trial* was splitted into 7 phases useful for analysis, according to the Perry's criterion [10]: Loading Response (AI), Midstance (AM), Terminal Stance (AF), Preswing (OP), Initial Swing (OI) Midswing (OM) and Terminal Swing (OF). In order to perform a quantitative analysis, for each gait profile, values corresponding to these gait phases were averaged, obtaining representative values for comparing subject's performance between conditions and guidance forces at each gait phase (Fig. 3).

Our analysis was focused in comparing these average values per gait profile at the different gait phases, and see differences between conditions and guidance forces, in order to assess the usability of recorded data as feedback for the patient as well for the therapist. Not all data recorded has utility when evaluating the implication of the patient in the movement of theirs limbs, because hip and knee have different roles at different phases of gait, and at some phases they are naturally less involved. We focused particularly in

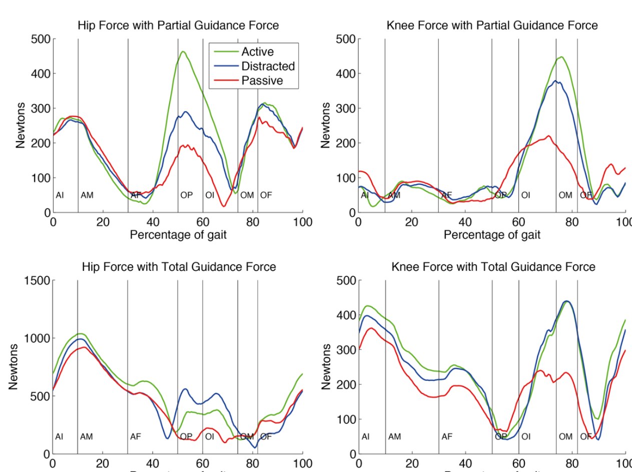

Fig. 2. Joint forces of one subject. From left to right columns: Hip and knee forces. From top to bottom rows: Partial and Total Guidance Forces.

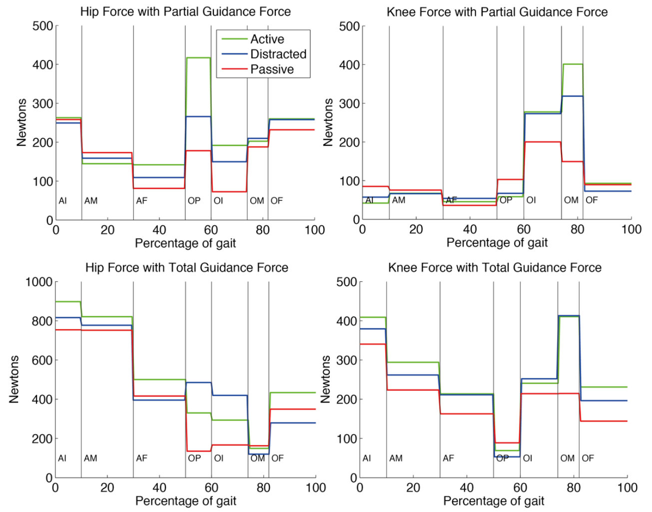

Fig. 3. Phase average forces of one subject. From left to right columns: Hip and knee average forcesper gait phase. From top to bottom rows: Partial and Total Guidance Forces.

the study of the joints in the gait phases in which they are involved: active hip flexion is required to bring the leg forward during the swing phase, active knee flexion during the early swing phase and knee extension during late swing phase. During the stance phase, most important activity is located at knee, which extension is required to bear the weight, whereas hip extension results from a combination of muscle activity and passive motion of the treadmill [4].

III. RESULTS

A. Joint angles

As can be seen in Figure 1, results shown that difference between joint angles was almost inappreciable for the all the subjects, regardless the gait phase, so we didn't find usability on kinetic data for this study.

B. Joint forces

Results shown high differences between measured forces in some cases, and less significant differences in others, but in the overall case, clear differences appear between conditions, at different gait phases.

1) Stance phase, knee joint: During stance phase, most important joint is the knee [4]; it must be actively extended to bear the weight of the patient. Results shown that when the Guidance Force was set to the Partial value, most of the subjects shown higher forces at this joint during AI (75%) and AM (62,5%) phases when walked passively than when walked actively or distractedly; during AF phase, same number of subjects (37,5%) shown higher forces when walking actively than when walking passively, and less number of subjects shown higher forces when walking distractedly (25%). When the Guidance Force was set to the Total value, most of the subjects shown higher forces when walking actively than when walking passively at AI (50%) and AM (75%) phases; at the AF phase, half of the subjects shown higher forces when walking actively, and the other half when walking passively. Only 1 subject shown higher forces when walking distractedly than when walking under the other conditions, and was during AI phase (Fig. 4).

2) Stance phase, hip joint: Movement at the hip joint is due to a combination of muscular activity and the movement of the treadmill. When Guidance Force was set to the Partial value, the number of subjects who shown higher forces when walking passively than actively is bigger during AI (37,5%) and AM (50%) phases, and equal during AF phase (37,5%); also the number of subjects (37,5%) who shown higher forces walking distractedly than actively is bigger during the AI and AM phases, but smaller (25%) during the AF phase. When the Guidance Force was set to the Total value, most of the subjects shown higher forces when walking actively than when walking under the other conditions during all the stance phase (62,5% for AI and 50% for AM and AF), difference between active and passive conditions smaller during AM and AF phases.

3) Swing phase, knee joint: Active knee flexion is needed during early swing phase to lift the foot from the floor, and active knee extension during late swing phase to approach the foot to the floor again. When Guidance Force was set to the Partial value, data recorded shown that during early swing phase (OP, OI), the number of subjects who shown higher forces when walking actively (37,5% and 50% respectively) was almost equal to the number of subjects who shown higher forces when walking passively (37,5% in both phases), being bigger than the number of subjects who shown higher forces when walking distractedly. During OM phase, most of the subjects shown higher forces when walking actively (87,5%), unlike during the late swing phase (OF), where subjects who shown higher forces when walking passively (62,5%) were more than others. When the Guidance Force was set to the Total value, subjects who shown higher forces when walking actively were more than others during most of the swing phase (62,5%, 50% and 62,5% for OI, OM and OF respectively); only during early swing phase (OP) number of subjects who shown higher values when walking actively was equal to the number of subjects who register higher values when walking passively (37,5%).

4) Swing phase, hip joint: Active hip flexion is needed to bring the leg forward during the swing phase. When Guidance Force was set to the Partial value, during the early swing phase (OP), subjects who shown higher forces walking actively were more (62,5%) than those who shown higher forces walking distractedly or passively; during OI phase, more subjects shown higher forces under passive condition (50%) than under other conditions, those who shown higher forces walking actively and distractedly were equal in number (25%); during OM phase, the number of subjects who shown higher forces during passive condition was equal to those who shown higher forces walking distractedly (37,5%), and both bigger than those who shown higher forces when walking actively (25%). During late swing phase (OF), number of subjects who shown higher forces during active condition was equal to the number of subjects who

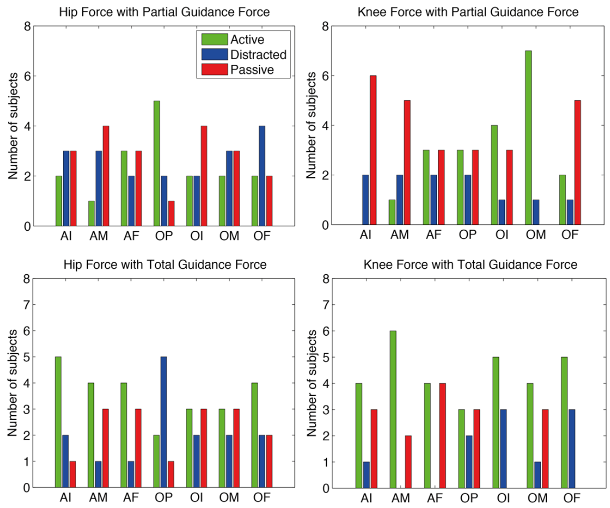

Fig. 4. Summary of results. From left to right columns: Hip and knee. From top to bottom rows: Partial and Total Guidance Forces. Bars represent the number of subjects who shown highest fores under determined condition.

shown higher forces during passive condition (25%), but both were smaller than subjects who shown higher forces during distracted condition (50%). When Guidance Force was set to the Total value, data recorded during OP phase shown that most of the subjects shown higher forces during distracted condition (62,5%); during rest of swing phase, number of subjects who shown higher values during active condition grows, becoming most during late swing phase (50%); on the other side, number of subjects who shown higher values when walking passively goes down (25%), while number of subjects who shown higher values during distracted condition keeps constant (25%).

Figure 4 shows bar diagram with these results.

IV. CONCLUSIONS

We have observed that joint angles are not meaningful biomechanical data to differentiate the analyzed conditions mainly due to the controlled trajectory approach that governs the exoskeleton. Although recent studies have shown that the patient is indeed able to alter the pattern imposes by the robot [7], with the rehabilitation improvements that this implies, these alterations are not significant enough for the aim of our study. On the other hand, differences between conditions can be detected by monitoring the joint forces, applying different detection thresholds, according to the phase of gait and amount of forces expected. In particular, it has been observed that when the guidance force is high, during stance phase, a subject walking actively should generate high forces at the knee joint, meanwhile a subject distracted should generate low forces; knowing this, the therapist can assess when the patient is focusing on the therapy and when not, establishing a low-forces threshold. Furthermore, with this phase-independent analysis, therapist can assess independently concrete aspects of the patients performance of gait, focusing therapy in enhance where necessary. In a hypothetical case, one patient could be performing a well gait pattern instead for the early swing phase, then, analyzing phases separately, therapist can focus therapy in this concrete aspect. Results also shown that knee joint force signal is more sensitive to variations of patient attention, resulting in a more relevant biomechanical marker to assess differences in the individuals' attention.

This new findings indicate that more accurate and customizable biofeedback techniques are feasible which in turn can increase its usability and ease of use. Such improvements can be directed towards the personalized definition and update of patient's baseline data with respect to their individual progress and degree of participation along the period of the robotic treatment.

Further work will consist on extending the current analysis to stroke survivors in order to determine the effect of attention to the task with end-users. The current results set the basis for the development of a novel biofeedback metric that can objectively provide means to enhance the active participation of the patient. Finally, the effectiveness of the presented biomechanical biofeedback analysis is to be assessed when compared to additional evaluation measures of patient's compliance and attention during robotic gait training.

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