Motion Capture and MultiBody Simulations to Determine Actuation Requirements for an Assistive Exoskeleton

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Keywords: Biomechanics, OpenSim, Exoskeleton.

Abstract: EUROSTAT's projections show that, by 2040, the people aged 65 or more will account to almost one fourth of the population. These statistics raise concerns over the sustainability of the society, so technological solutions have been emerging to prolong the active age of European citizens. One of the main impairments for elders is an increasing difficulty in performing daily lower-limb activities (i.e. walking, climbing stairs) due to Sarcopenia, among other issues. Therefore, the authors are developing an active exoskeleton whose sole purpose is to assist the gait of an elderly person. The proposed system is based on a low-profile design, allowing a smaller frame that allows the device to be worn beneath loose clothing, making it more desirable to wear in public by reducing social awkwardness. This article shows the methodology used to determine the actuation requirements for the exoskeleton. Two subjects performed a number of trials depicting daily life activities in a biomechanics laboratory that acquires motion sensor and force-plate data. Each activity was performed with additional weights to emulate the presence of an exoskeleton. The data was used in a multibody simulation program (OpenSim) to determine the requirements (angular speed, torque) for the actuation system in the exoskeleton.

1 INTRODUCTION

The ageing process in the human being results in several changes in the musculoskeletal system. Among other effects, the muscles shrink and lose mass *i.e. Sarcopenia*, the number and size of muscle fibers decrease, the tendons and cartilages become less tolerable to stress, the heart lowers the speed at which it can pump blood and the bones lose mass, becoming more prone to fractures (des, 2017). One of the first major symptoms that appear with ageing is an irregular gait and decreased gait speed (Riley et al., 2001).

The appearance of these symptoms usually results from an increasingly sedentary life. Consequently, a sedentary life will aggravate the aforementioned changes in muscle and bone mass reductions. An absence of muscle stimulation results in loss of muscle mass (Fiatarone and Evans, 1993) and the lack of stress applied to human bones will prevent the piezoelectric effect and mechanotransduction that maintains their density (Muscolino, 2016).

This results in a continuous self-feeding cycle where the symptoms contribute directly to worsening the conditions, as shown in Figure 1.

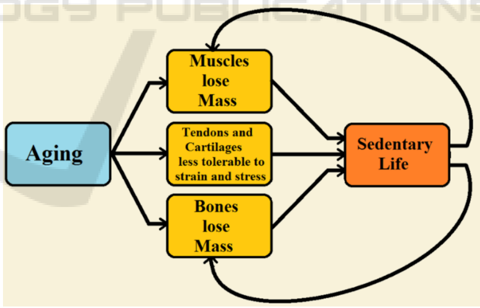

Figure 1: Cycle of symptoms and consequences during aging.

Additionally, adopting a sedentary life and moving less frequently also decreases a person's confidence and motor control, increasing the chances of suffering from falls (Steadman et al., 2003). The lack of an active life is also associated with social isolation (Shankar et al., 2011). The end result is a lower quality of life that can result in depression and other psychological disorders (Steptoe et al., 2013).

There are classical solutions for medium mobility impairment, such as crutches and walkers. However they occupy the upper limbs which results in a drastic

Pina, D., Gabriel, J. and Natal, R.
Motion Capture and MultiBody Simulations to Determine Actuation Requirements for an Assistive Exoskeleton.
DOI: 10.5220/0007403601830191
In *Proceedings of the 12th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2019)*, pages 183-191
ISBN: 978-989-758-353-7

change of lifestyle and the misuse of these solutions can cause injuries in the long term. Moreover, the mobility walkers can be difficult to use within tight spaces such as house interiors and bathrooms.

Due to an increase in life expectancy and decrease of birth-rate, many developed countries are suffering from an ageing population. Europe is the continent with the oldest population in the world. According to a recent EUROSTAT report (EUROSTAT, 2014), close to 20% of the European population is aged 65 or above. This results in almost 85 Million people in that age bracket. Within these, 23% show a moderate difficulty while walking and 21% show severe difficulty, as seen in Figure 2.

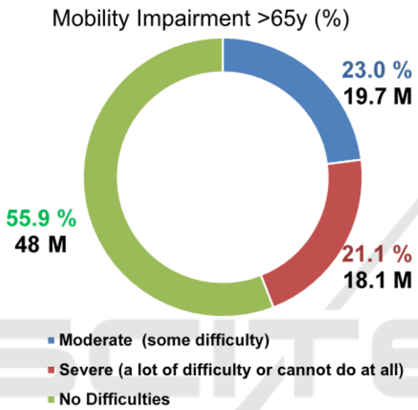

Figure 2: Proportions and number of people (in millions) in the European Union aged 65 years or older with moderate or severe mobility impairment, according to a 2014 EUROSTAT study (EUROSTAT, 2014).

EUROSTAT's projections also show that, by 2040, the people aged 65 or more will account to almost one fourth of the population (EUROSTAT, 2017).

Therefore, the ratio between working age (18-65 years old) and non-working age people would be close to 2 to 1, which raises questions regarding the sustainability of the European society (Commission, 2015). Due to this growing concern, many studies and initiatives (Walker, 2010), (HARTLAPP and SCHMID, 2008), (Peine et al., 2014) have emerged in order to extend the active age for European citizens.

Moreover, the age evolution projections would increase the number of people aged 65 and over with moderate mobility difficulties from 20 Million to over 35 Million.

It is therefore of the utmost importance to develop solutions that contribute to solving the several problems of mobility within the 3rd and 4th ages, which are aggravated by the ageing population in the European Union.

The proposal for the project is to develop a low-profile active exoskeleton with a smaller range of utilization than other active exoskeletons currently in the market (such as the HAL (Sankai, 2006)), which is uniquely to assist an elderly person's gait and other daily life activities such as climbing stairs.

By focusing on these activities, it is possible that an exoskeleton that assists the lower limb activities can be achieved with a small frame, which could go unnoticed if the user is wearing loose clothes.

This paper refers to determining the actuation requirements to assist the user of the exoskeleton being developed.

An explanation for the methodology used to design the mechanical frame can be seen in (Pina et al., 2018). Because the exoskeleton is aimed at helping the movement in the lower limbs in people with a reduced degree of strength and mobility, the system proposes to assist the lower limbs' biomechanical forces by 50%. The exoskeleton is planned to wear a total of 20 kg, though it is designed to support itself by extending into the ground.

2 THEORETICAL FRAMEWORK

The exoskeleton is designed to support its own weight. However, when the exoskeleton is equipped, the combined system composed of human body and exoskeleton is bound to demand additional torque than the human body alone. This happens because the total weight is higher, so the torque levels required to perform daily life activities will also be greater.

The formula for the torque is expressed in equation 1:

$$\tau = I \times \alpha \tag{1}$$

Where τ is the torque in N.m, I is the moment of inertia in $kg.m^2$ and α is the angular acceleration.

Given I as the moment of Inertia dependent on the mass m and distance r to the pivot:

$$I = m \times r^2 \tag{2}$$

therefore, the torque τ for a given movement depends on the mass m, distance r and angular acceleration α:

$$\tau = m \times r^2 \times \alpha \tag{3}$$

If the purpose of the exoskeleton is to provide the same natural movements that are performed on a daily basis, then the angular acceleration α is ideally the same, and r is constant because the exoskeleton adapts its length to the user's limbs. Therefore, an increment on the mass m of the bodies being moved results in an increment on the torque τ.

So the sum of torques required to move a system composed of human body and exoskeleton is greater than the sum of torques required to move the human body:

$$\sum \tau_{(human\,with\,exoskeleton)} > \sum \tau_{(human)} \qquad (4)$$

The system proposes to assist the human movement in daily activities in close to 50%, so the torque provided by the exoskeleton actuators must be designed to perform 50% of the system combined of human with exoskeleton.

To achieve these values, a number of trials with human subjects was made with no weights and then with attached weights to emulate the weight of the exoskeleton.

3 MOTION CAPTURE DATA ACQUISISTION

The trials were performed in a laboratory capable of doing motion capture through cameras and markers placed on the subjects. There are also four force plates that exist to determine the ground reaction forces for gait trials, and are arranged according to Figure 3.

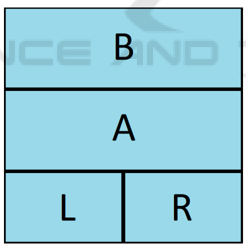

Figure 3: Arrangement of the force plates in the biomechanics laboratory.

During a gait trial, if the first force plate to be stepped on is plate ”L”, then it is assumed that plate A will be stepped on by the right foot and plate B will be stepped on by the left foot. This arrangement allows the system to acquire the ground reaction forces for a full gait cycle.

The trials were performed by two subjects: a female with a weight of 52.4 kg and height of 1.52 m, and a male with a weight of 63.8 kg and a height of 1.73 m.

As seen in (Pina et al., 2018), the mechanical frame of the exoskeleton weights close to 8 kg. In order to include the weight of the backpack with actuators, batteries and other subsystems, the exoskeleton simulation trials were performed with the subjects carrying an additional weight of 20 kg. The trials were performed with a weight distribution similar to the exoskeleton frame, in order to approach the dynamic behavior of the exoskeleton. The subjects attached different weights throughout the lower limbs and its distribution can be seen in Figure 4.

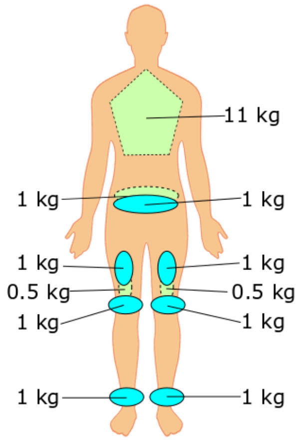

Figure 4: Distribution of the attached weights to approach the weight dynamics of the exoskeleton developed.

Pictures of the female and male subjects with and without the attached weights can be seen in Figure 5.

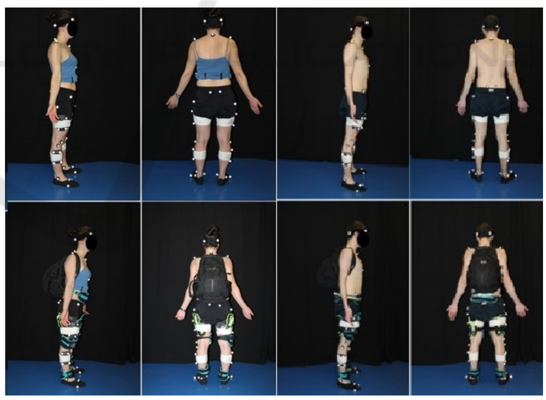

Figure 5: Pictures of the female and male subjects. On top, with normal clothing and no added weights. On the bottom, with the attached weights and backpack.

The subjects performed the trials described in Figure 6. The sitting and standing results are not considered in this work because they did not contribute to the end results.

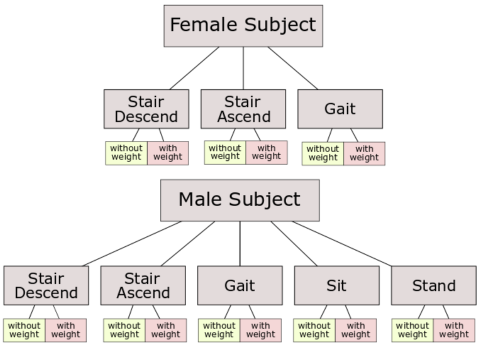

Figure 6: Diagram of the trials performed for each subject.

Figure 7 shows a gait trial performed by the female subject, with and without the additional weights.

Figure 7: Pictures of the female subject performing gait trials with normal clothing on the left and attached weights on the right.

To perform the stair trials, a set of mock-up stairs was built with brick and wood to provide a safe method to simulate stair ascend and descend. The stair climb and descend cycles have the same description as gait cycles. Each leg performs a stance phase (between the foot making contact with one step and lifting off to the next step) and swing phase (between the foot lifting off one step and reaching the next). There are two mock-up steps: with a height of 40 cm and a second with a height of 80 cm. Although these mock-up stairs are higher than usual stairs in modern houses, this way they present a "worst-case scenario", as higher stairs are prevalent in older houses or public buildings. The lower set of stairs was placed in force plate A (from Figure 3) and the taller set was placed in force place B. The acquisition software for the force plates was then tuned to subtract the weight of the mock-up steps. To complete the cycle after the taller step, there was a wooden block to complete the the ascend or initiate the descend movements. The wooden block was not placed over force plates.

In order to organize the final simulation results, the subjects were instructed to climb the mock-up stairs with the right leg on the lower step, and then to descend the stairs with the right leg first.

Figure 8 shows pictures of the tests for stair ascend and stair descend.

Figure 8: Pictures of the female subject performing stair trials with normal clothing on the left and attached weights on the right. The top two pictures show stair climbing while the bottom pictures show stair descending.

4 OpenSIM WORKFLOW

The software used to perform the multibody simulations is the OpenSim 3.3 Simulation Toolkit developed by Scott Delp (Delp et al., 2007). The software is open source and is capable of performing multibody simulations for biomechanical applications. The muskuloskeletal tridimensional model used for the simulations is the reference Gait2392 (Delp et al., 1990), which is based on anatomical data provided by several studies (Friederich and Brand, 1990), (Hoy et al., 1990). Gait2392 has 23 degrees of motion and was designed to perform lower limb simulations.

OpenSim takes the marker data and performs Inverse Kinematics to translate into motion data for the Gait2392 model, in the form of angular position per joint through time. There is also a Scaling function, which uses marker data and the subject's weight to customize the Gait2392 model. With the scaled model, motion data and ground reaction forces from the force plates, it is possible to perform Inverse Dynamics which provides the torque values for each joint.

However, the Inverse Dynamics procedure induces virtual residual actuators (consisted of torques and forces applied to the pelvis) to help stabilize the model due to data acquisition errors in the motion capture system and force plates. In complex models like the Gait2392 using complex motions, the residual actuators often assume large values, which significantly reduces the validity and precision of the calculated torques.

The Residual Reduction Algorithm (RRA) uses the Computer Muscle Control (CMC) algorithm to control the torque applied by point actuators placed in each joint. The CMC algorithm was developed to calculate muscle activations for any given movement through power-saving paths, as a biomimetic approach (Seth et al., 2011). At the same time, the RRA makes slight modifications the motion data and proposes mass changes to each body in order to reduce the values of the residual actuators.

Figure 9 shows the regular workflow for performing simulations using RRA:

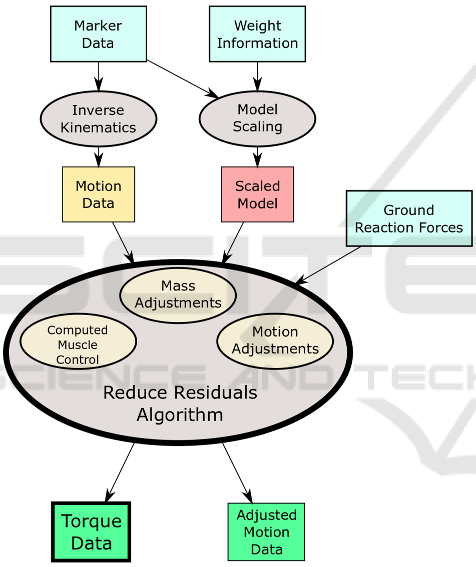

Figure 9: Workflow for the OpenSim Simulation Toolkit to achieve precise values for joint torques using RRA.

According to the software developers, the results are only valid if the values for residual forces and error displacements are below pre-defined thresholds. Therefore, the results obtained in this article were achieved by tuning the simulation timings to fit the thresholds for the residual actuators.

For performing the simulations with the additional weights, the exoskeleton components described in (Pina et al., 2018) were adapted to the body measurements of the male and female subjects. Afterwards, the exoskeleton components were ported and adapted into the Gait2392 model with the correct values for geometry, mass, center of mass and inertia. The weight distribution is different between the weights attached to the subjects in the trials and the virtual exoskeleton. To compensate for this difference, the RRA procedure for mass changes was repeated for each virtual model until the proposed changes were minimal. At the moment of writing, the mass change procedure is only possible through command line and is not available through the software's GUI.

The models used the OpenSim simulations can be seen in Figure 10.

Figure 10: From left to right: male subject with exoskeleton, female subject with exoskeleton, male subject without exoskeleton, female subject without exoskeleton.

5 OpenSIM RESULTS

The results presented in this section show the torque values for the hip and knee joints for each activity and for each subject. These joints are planned to be actuated and assisted by the exoskeleton. For some trials, the ankle torque is also shown. The ankle joint is not actuated by the system, but the torque differences may be a concern. However, a large proportion of the ankle plantar flexion torque originates from passive elastic forces from extending the Soleus muscle. Also, many types of footwear limit the plantar flexion so its importance in this system is considered partially reduced. Each result graphic shows a joint torque from a trial with weight and another joint torque from the equivalent trial without weight, to provide better means of comparison.

The OpenSim's graphics creator utility defines a positive torque for hip flexion and negative torque for hip extension. For the knee, flexion is negative and extension is positive.

In some results, the same trial for the same joint is split into two simulations. The reason for this is because in some simulations the values for the residual actuators and displacement errors would start to increase.

In the following torque graphics, the blue and green lines show a result without additional weight and in red a result with additional weight.

5.1 Gait Results

The following results were obtained through the OpenSIM RRA simulations with data taken from the gait trials. A screenshot of the male model with and without the exoskeleton can be observed in Figure 11

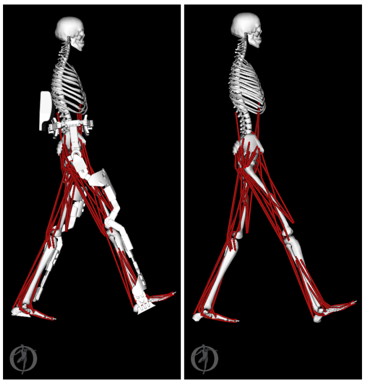

Figure 11: Screenshot of the simulation with the male model with the exoskeleton on the left and without the exoskeleton on the right.

Hip Joint
Figure 12 shows the torque results for the hip joint flexion/extension in the female subject, during the gait trials. The higher positive torque values in the hip flexion correspond to the beginning of the swing phase.

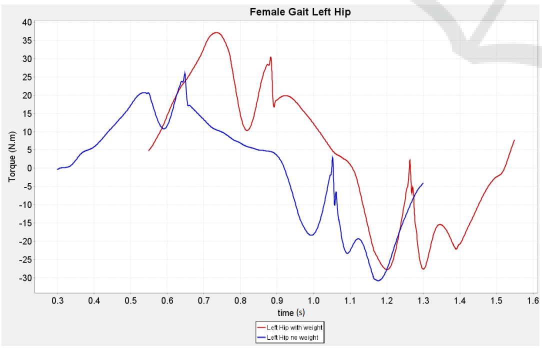

Figure 12: Hip Extension/Flexion torque values for the gait trials with the female subject.

With the female subject, the additional weight causes a difference of 12 N.m in the left hip flexion. Hip extension (negative values) is showing larger torque values without weight. A possible explanation for this is the subject assuming a faster walking pace.

Figure 13 shows the same trials for the male subject.

The male subject shows a 12 N.m difference in the right hip flexion.

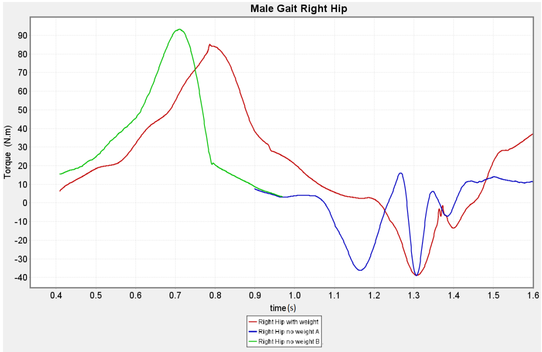

Figure 13: Hip Extension/Flexion torque values for the gait trials with the male subject.

Knee Joint
The torque results for the female subject's knee joints during gait are shown in Figure 14. The higher positive torque values in the knee correspond to the moment of heel contact.

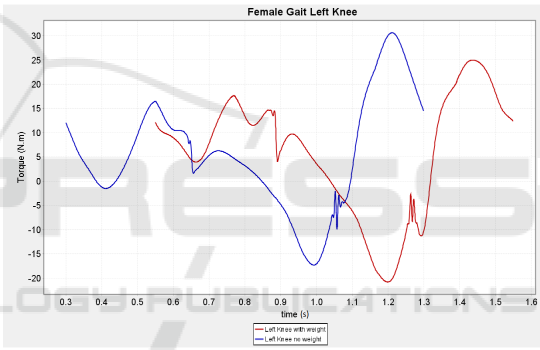

Figure 14: Knee Extension/Flexion torque values for the gait trials with the female subject.

The knee results in the female trial do not show significant torque differences, and the same was observed with the male trials.

5.2 Stair Ascend and Descend Results

The stair ascend and descend simulations could not be resolved for a full "stair" cycle. Due to the generally increased complexity of the movements, the simulation periods are reduced to keep the residual actuator values within the pre-established thresholds determined by OpenSim's developers. Therefore, it is expected for the joint results in one side to match half a cycle and the other side to match the other half (e.g. left leg joints show the swing phase and the right leg joints show the stance phase). The following graphics show the results with a larger difference observed between trials with and without weight.

Screenshots of the male model with and without the exoskeleton during the simulations with stairs can be observed in Figure 15

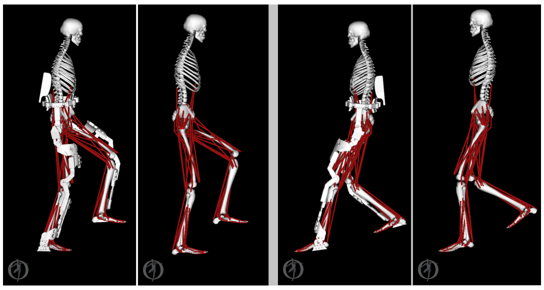

Figure 15: Screenshot of the simulation with the male model with and without the exoskeleton while climbing stairs on the left and descending stairs on the right.

Hip Stair Ascend

Figure 16 shows the hip results for the male subject.

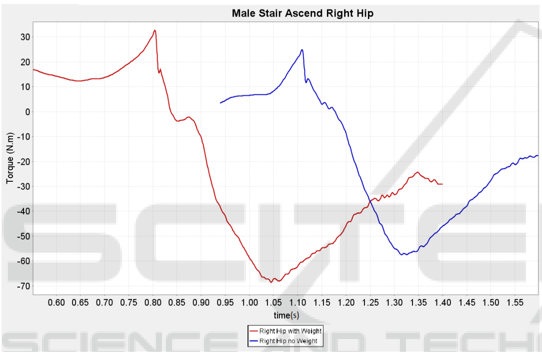

Figure 16: Hip Extension/Flexion torque values for the stair ascend trials with the male subject.

The maximum torque values for the male subject's right hip shows a 10 N.m difference in extension during the stance phase.

Knee Stair Ascend

Figure 17 shows the knee torque values for stair ascend with the female subject.

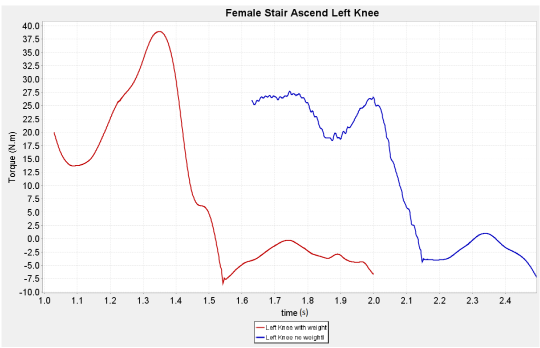

Figure 17: Knee Extension/Flexion torque values for the stair ascend trials with the female subject.

The weight trials show a 22 N.m increase in maximum torque for knee extension during the swing phase with the left knee.

Hip Stair Descend

Figure 18 shows the hip joint torque values for the male subject during the stair descend trial.

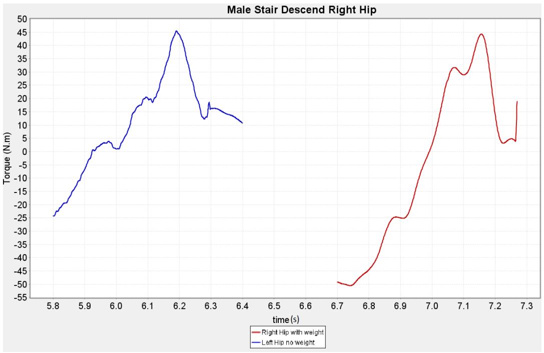

Figure 18: Hip Extension/Flexion torque values for the stair descend trials with the male subject.

The male subject results show a 20 N.m difference in the right hip extension.

Knee Stair Descend

The stair descend trial with the knee joint shows the largest torque differences between the results with and without weight. The knee extension peak values correspond to the moment when the subjects' feet make contact with the lower step. This moment matches the highest torque observed in any of the movements studied in the trials.

Figure 19 shows the same trials for the male subject. The knee torque differences with and without weight are similar between the male and female subject. The male subject shows a difference of 50 N.m in the left knee.

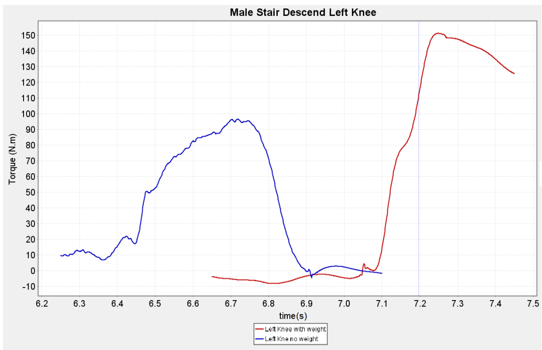

Figure 19: Left Knee Extension/Flexion torque values for the stair descend trials with the male subject.

6 CONCLUSIONS

Although the subjects were instructed to perform the same movements, the additional weights created a difference in the body dynamics, and therefore the movements themselves. For this reason, some tests show large differences in torque values between trials with and without additional weight.

The Exoskeleton proposes to assist the movement in the daily activities by 50%. To achieve this, the maximum torque values from the actuation system should be able to perform 50% of the maximum torque values for a given movement without the weights ($\tau(t_{max})_{normal\,body}$), plus the difference in torque for the same movement with the weights($\Delta\tau(t_{max})_{body\,with\,exoskeleton}$).

Therefore:

$$\tau(max)_{actuation\,system} = \\ = \tau(t_{max})_{normal\,body} \times 50\%) + \Delta\tau(t_{max})_{body\,with\,exoskeleton} \quad (5)$$

The aforementioned torque values and torque differences are observed in the following trials:

Hip Extension:
Stair ascend with male subject: 60 N.m without weight and $\Delta\tau$ 10 N.m.
$\tau(max)_{actuation\,system} = (0.5 \times 60) + 10 =$ **40 N.m**

Hip Flexion:
Stair Descend with male subject: 50 N.m without weight and $\Delta\tau$ 20 N.m.
$\tau(max)_{actuation\,system} = (0.5 \times 50) + 20 =$ **45 N.m**

Knee Extension:
Stair Descend with male subject: 100 N.m without weight and $\Delta\tau$ 50 N.m.
$\tau(max)_{actuation\,system} = (0.5 \times 100) + 50 =$ **100 N.m**

Knee Flexion:
Gait with male subject: 27 N.m without weight and $\Delta\tau$ 3 N.m.
$\tau(max)_{actuation\,system} = (0.5 \times 27) + 3 =$ **16.5 N.m**

The largest requirement for torque assistance from the exoskeleton is the knee extension with a value of 100 N.m. Given the large difference between the torque requirement for this specific movement (knee joint in stair descend) and the torque requirements for the other movements, the 50% assistance value may not be met in this case, or additional types of solutions may be studied. For example, since the knee extension during stair descend is performing negative work, the same torque can be obtained through a controllable brake.

With this data, it will be possible to develop an actuation system that is neither under or overengineered for the exoskeleton. This process can therefore be able to save time and costs during the exoskeleton development.

ACKNOWLEDGEMENTS

The authors would like to thank the “Ministério da Ciência, Tecnologia e Ensino Superior – Fundação para a Ciência e a Tecnologia, Portugal” for the funding provided by the research project “LAETA – UID/EMS/50022/2013”.

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