Reduction of muscle activation in the right leg during gait using a passive exoskeleton

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Abstract – Simulations permit adding external elements, such as assistive devices, and observing their behavior. OpenSim is a platform that can model and simulate musculoskeletal systems. In this project, we will explore how parameters of an assistive device based on an elastic element may influence muscle activation during walking; similar to the presence of Collins et al. (2015) and Sawicki et al. (2016) research. We performed all the analysis using experimental data form a RRA optimized model in OpenSim to determine optimal stiffness and optimal resting length as well as to perform a geometrical analysis of the proposed assistive device. We explored the effect of the assistive device and its parameters on four different muscle groups (plantar flexors, dorsiflexors, knee flexors and knee extensors) and found optimal stiffness and rest length for the proposed device's elastic band.

Keywords - Ankle, exoskeleton, stiffness, resting length, geometry.

I. INTRODUCTION

During human evolution, the musculoskeletal system has always sought to be efficient during walking, in other words, the musculoskeletal system uses the least amount of metabolic energy to carry out movements, however, any change generates gait cycle pathologies. Currently, passive exoskeletons seek to solve the pathologies of the gait cycle [1,2].

In this project, we will study a similar device as present by Collins[1] and Sawicki [2] made from an extension spring placed around the ankle joint. While different models have been proposed throughout the field, we seek to present our own take on an elastic band exoskeleton for the ankle joint.

II. METHODS

We performed all analysis on the right leg of an OpenSim model to which RRA had already been applied. Through the use of static optimization, we investigated how an ideal passive exoskeleton affected the muscle distribution problem. Like this, we started by analyzing how the stiffness and resting length of the extension spring affected the activation of muscle groups responsible for the movement of the ankle joint during gait. It is important to mention that the initial geometric model of the exoskeleton is an ideal representation, meaning that it follows the same geometric path as the right soleus. For this reason, a second geometric study was performed in which a more realistic exoskeletal model was developed (Figure 1). Through the modification of the elastic band's (extension spring) geometry path, we were able to represent a realistic external exoskeleton, allowing us to determine the optimal elastic band stiffness alongside its ideal resting length in order to minimize muscle activation during gait.

a. OPTIMAL STIFFNESS

To determine the elastic band's optimal stiffness, we performed static optimization on the provided model using 9 different stiffness values spanning 2 orders of magnitude. Stiffness values selected were [10, 25, 50, 75, 100, 250, 370, 500, 1000] kN/m in order to get a broader scope into how large and small stiffness values affected muscle activation. Values beyond 1000kNm were excluded as they resulted in maximum muscle activation for the dorsiflexors.

Muscle activation of each of the muscle groups studied were then plotted for the varying elastic band stiffnesses and an integral of overall muscle activation was calculated for each muscle group to determine total muscle activation for varying elastic band stiffnesses.

Polynomial regression of grade 2 was then performed on the overall activation data to determine the minimum muscle activation alongside its elastic band stiffness.

Finally, static optimization was ran one last time using the optimal stiffness value obtained during quadratic regression of total muscle activation. This was then plotted alongside the 9 initial values for validation purposes.

b. OPTIMAL RESTING LENGTH

Once the optimal stiffness was obtained, we used this value to determine the optimal resting length of the elastic band. For this analysis we selected resting lengths close to the elastic bands' original size. Values selected were [285, 290, 295, 300] mm. Static optimization was performed for each one of these values and overall muscle activity was calculated in the same way as done for the optimal stiffness determination. A quadratic regression model was applied to the overall muscle activation and optimal resting length was determined.

Once again, static optimization was ran using the optimal resting length and the results were plotted alongside the original 4 selected values.

c. GEOMETRY ANALYSIS

In order for this device to be attachable to the human leg, a non-intrusive geometric model had to be developed in order to place the elastic band parallel to the calf. In this way, the geometric path of the elastic band was modified within OpenSim to resemble Figure 1. Once a defined geometry was established, static optimization was used to determine the optimal elastic band stiffness and resting length for this modified geometric path.

Figure 1 | Proposed model of the passive exoskeleton using an elastic band. The exoskeleton would attach to any arbitrary sneaker or shoe through its bootstrap, making it only necessary for the subject to attach the device below the knee, resulting in minimal discomfort of the foot.

III. RESULTS

Results were obtained using OpenSim's built-in Static Optimization tool, data for all simulations was exported and plotted using the assistance of MATLAB.

a. OPTIMAL STIFFNESS

There is a clear trend when it comes to elastic band stiffness and its force throughout gait cycle. Energy stored in the elastic band during loading response and initial single leg stance is converted to force and applied during terminal stance to propel the body forward. Like this, the stiffer the spring, the more energy it can store and therefore the higher force it can exert during terminal stance (Figure 1).

In this way, the force applied during terminal stance by the elastic band helps compensate for the force required to lunge forward into the initial contact of the opposing leg, therefore reducing the activation of the muscles that were originally responsible for this task (plantar flexors).

When observing the activation of the plantar flexors (Figure 3 – PF), the effect of the elastic band is favorable, decreasing both the overall activation and the initial activation time. However, after closer inspection it can also be seen that peak activation varies slightly, probably due to the resting length of the elastic band being reached and therefore requiring the soleus to take over.

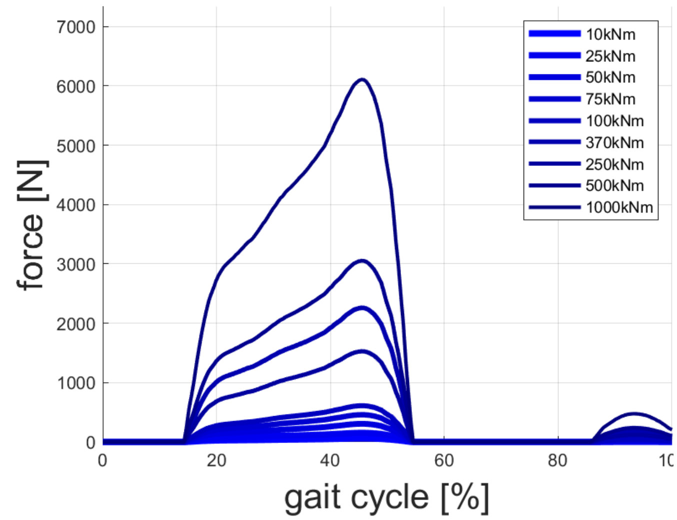

Figure 2 | Force exerted by elastic band over gait cycle for different spring stiffnesses. Peak force was obtained with a stiffness of 1000kNm without over-activation of the dorsiflexors. There is a clear trend, as elastic band stiffness increases, the energy stored increases and therefore it can generate greater force.

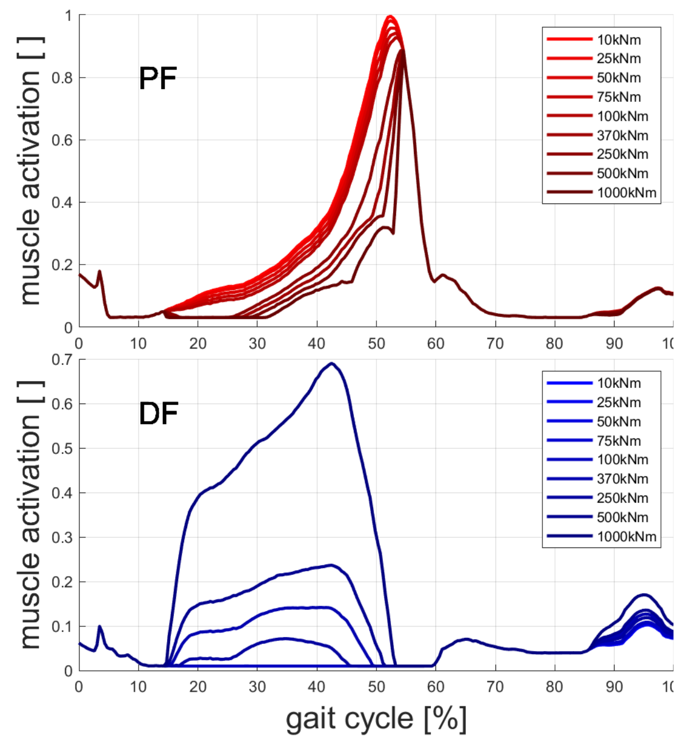

Figure 3 | Muscle activation over gait cycle of plantar flexors (PF) and dorsiflexors (DF) assisted by an elastic band exoskeleton for different stiffnesses. A clear decrease in plantar flexor activity is seen with an increase in elastic band stiffness. The opposite can be said about the dorsiflexors, where muscle activation increases with elastic band stiffness.

Furthermore, while the increase in the stiffness of the elastic band shows a decrease in the overall plantar flexor activation, it is not possible to completely replace the force provided by the plantar flexors, at least at an elastic band rest length of 295mm.

Nonetheless, the effect of the elastic band affects not only the muscles it replaces but also the muscles it opposes. While the effects of the elastic band can be favorable for the plantar flexors (Figure 3 – PF), an opposite effect occurs in the dorsiflexors (Figure 3 – DF) whose activation increases with the increase of the stiffness of the elastic band. Moreover, when comparing Figures 2 and 3 – DF, a clear resemblance can be spotted which indicates that the dorsiflexors are compensating for the over-stiffness of the elastic band and therefore, a higher activation is needed to stretch the elastic band.

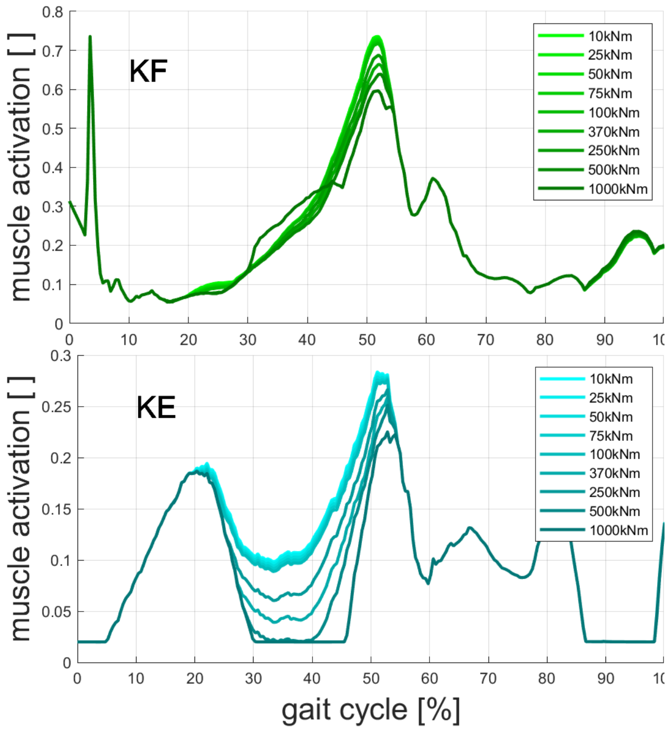

Figure 4 | Muscle activation over gait cycle of knee flexors (KF) and knee extensors (KE) assisted by an elastic band exoskeleton for different stiffnesses. Muscle activity seems consistent for knee flexors (aside from extreme values). Knee extensors' muscle activity decreases with increasing elastic band stiffness.

The two other groups observed during the analysis were the knee flexors (KF) and knee extensors (KE) (Figure 4). Whilst the effect of the elastic band stiffness was minimal on the knee flexors group, a clear impact can be seen on the knee extensor, where muscle activation dropped considerably during terminal stance for the higher stiffness values.

When observing Figure 5, overall activation for the plantar flexors, dorsiflexors, knee flexors and knee extensor are plotted individually. The black tick line represents the sum of the activation of all muscle groups, resulting in a curve that represents total muscle activation during gait. The black tick line is the product of performing quadratic regression on the data points plotted (black crosses). In this way, after performing quadratic regression for the stiffnesses simulated, an optimal value of stiffness appears, for which total muscle activation is minimal (Figure 5). The value of this stiffness is exactly 371,212.12Nm, however it has been rounded off to 370kNm for simulation purposes.

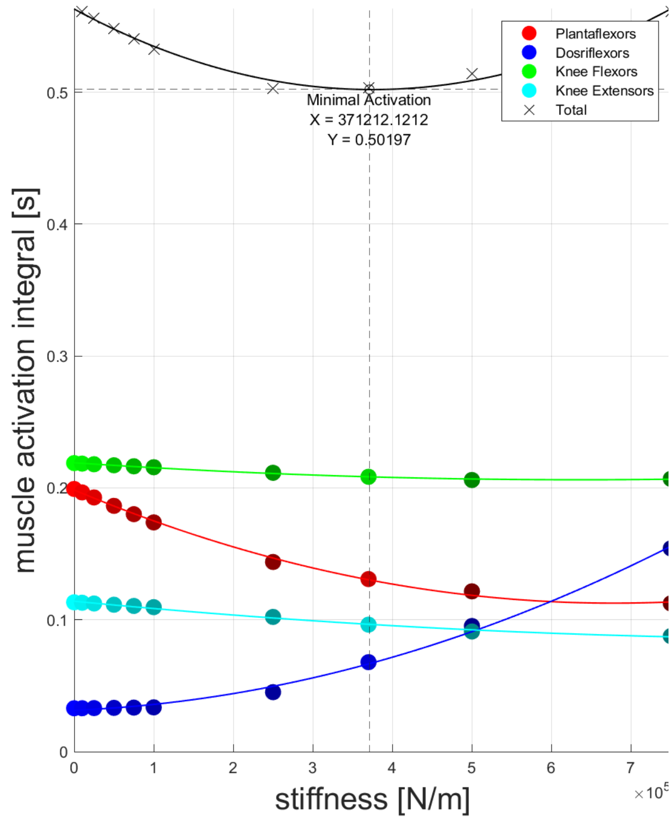

Figure 5 | Overall muscle activation of plantar flexors, dorsiflexors, knee flexors and knee extensors group muscles for varying elastic band stiffness. Plantar flexors' (**red**) overall activation decreases with the increase in elastic band stiffness, the same can be said for knee flexors (**green**) and knee extensors (**cyan**) but to a lower degree. Dorsiflexors' (**blue**) overall activation increases with elastic band stiffness, due to increased muscle demand required to stretch the elastic band. Overall activation (**black**) of all muscle groups shows to have a point of minimum activation with a stiffness of about 370kNm.

b. OPTIMAL RESTING LENGTH

Using the optimal stiffness of 370kNm, optimal resting length of the elastic band was determined.

Muscle activation for plantar flexors (PF), dorsiflexors (DF), knee flexors (KF) and knee extensors (KE) were plotted during gait cycle for varying elastic band rest length (Figure 6). Special attention must be brought towards the trade-off in muscle activation between the plantar flexors and the dorsiflexors. As elastic band rest length increases, plantar flexor activation increases and dorsiflexor activation decreases. In this way, for short elastic band rest lengths (285mm) we can see minimal activation of the plantar flexors, which suggest an even shorter elastic band rest length could result in the elimination of plantar flexor activation. However, a shorter elastic band rest length would mean higher activation from the dorsiflexors (which are already at a 0.8 peak at 285mm) which could easily reach excessive activation for this muscle group.

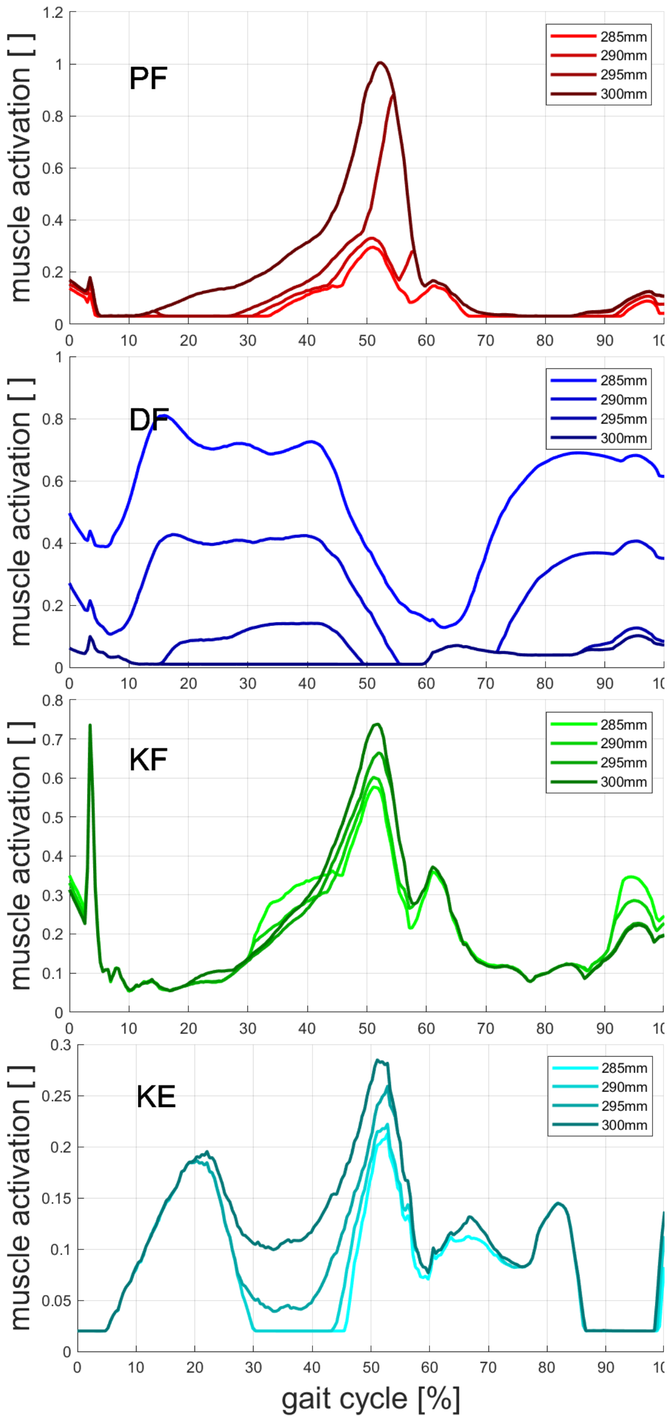

Figure 6 | Muscle activation over gait cycle of plantar flexors (PF), dorsiflexors (DF), knee flexors (KF) and knee extensors (KE) assisted by an elastic band exoskeleton for different elastic band rest lengths. A clear trade-off can be seen between the plantar flexors and the dorsiflexors when the elastic band rest length is altered. A more significant effect can be seen, this time in both the knee flexors and extensors, where muscle activation decreases with a decrease in elastic band rest length.

Overall muscle activation was plotted as seen in figure 7. Note that the trend for plantar flexors and dorsiflexors are reversed when compared to Figure 5. That is, when the independent variable increases, plantar flexor activation increases and dorsiflexor activation decreases.

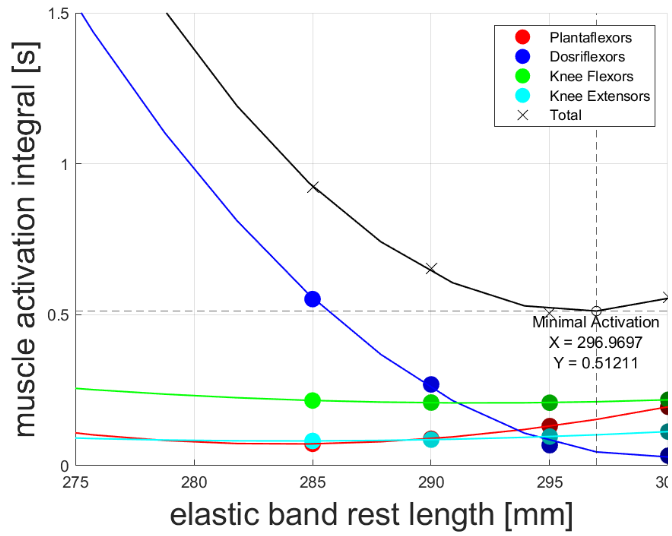

Figure 7 | Overall muscle activation for different elastic band resting lengths. Muscle activation proves to show minimum activation at an elastic band rest length of about 295mm.

By varying the elastic band rest length, we were able to calculate the overall activation for each muscle group, resulting in the total muscle activation for different elastic band rest lengths. Figure 7 shows the total muscle activation (black tick line) where a minimal point at an elastic band rest length of 296.96mm can be seen.

c. GEOMETRY ANALYSIS

For the geometry analysis of a realistic external exoskeleton, modifications were done on the geometry path of the elastic band as seen on Figure 8.

Figure 8 | Elastic band geometry simulated in OpenSim. The elastic band was modeled in a more realistic way, offsetting it from the calf in order to resemble the exoskeleton proposed in Figure 1.

The modification of the geometry path altered both the optimal stiffness of the elastic band as well as its optimal resting length.

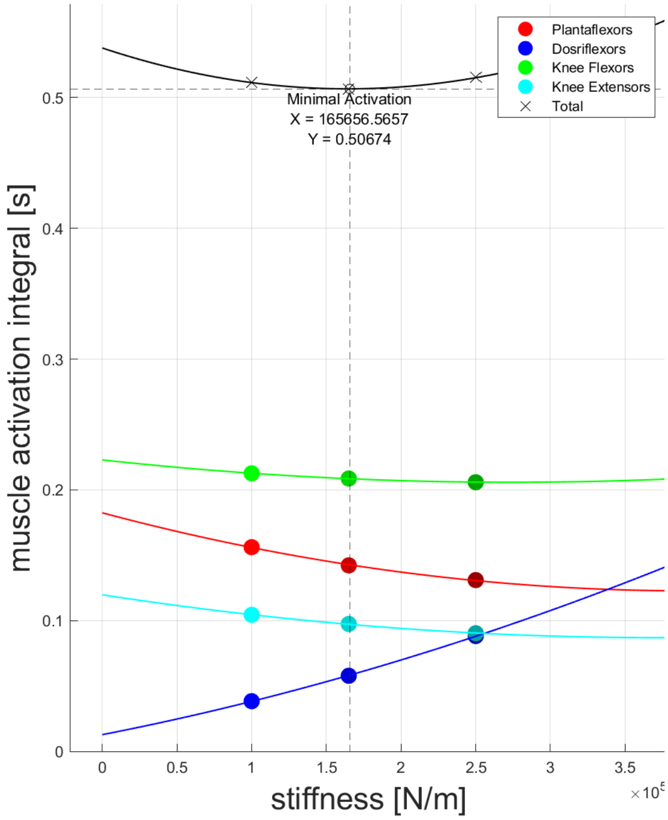

Figure 9 | Overall muscle activation of plantar flexors, dorsiflexors, knee flexors and knee extensors group muscles for varying elastic band stiffness. An optimal point that minimizes muscle activation can be seen at an elastic band stiffens of 165,656.57Nm

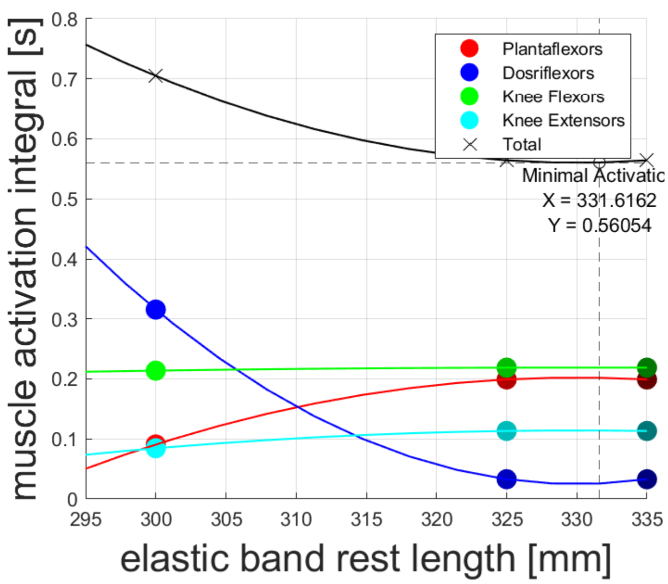

Figure 10 | Overall muscle activation of plantar flexors, dorsiflexors, knee flexors and knee extensors group muscles for varying elastic band rest length. An optimal point that minimizes muscle activity can be seen at an elastic band rest length of about 331.6mm.

For this new geometry, optimal elastic band stiffness shifted to the left, resulting in an optimal stiffness of about 165kNm (Figure 9), while optimal elastic band rest length shifted slightly to the right to an optimal value of about 332mm (Figure 10).

IV. DISCUSSION & CONCLUSION

We have analyzed how the implementation of an ideal and a realistic passive exoskeletal model affects muscle activation during gait cycle. It is evident that the addition of an elastic band (extension spring) helps reduce the activation of muscle groups such as the plantar flexors, particularly during terminal stance. However, an opposite reaction can be seen on antagonist muscle groups such as the dorsiflexors. In this way, the development of an elastic band exoskeleton must be assessed with extreme care as slight changes in parameters such as elastic band stiffness and elastic band rest length show considerable effects in the overall muscle activation during gait.

These effects can be seen beyond the plantar flexor and dorsiflexor muscle groups. Proximal muscle groups such as the knee flexors and the knee extensors are also vulnerable to changes when an ankle joint exoskeleton is introduced. Moreover, we have seen the effect of varying elastic band stiffness and elastic band rest length on the four muscle groups previously mentioned showing that for an increase in elastic band stiffness: plantar flexors, knee flexors and knee extensors activation decreases and dorsiflexor activation increases, and for an increase in elastic band rest length: plantar flexors, knee flexors and knee extensors activation increases and dorsiflexor activation decreases. In addition, further assessment of the proximal muscle groups show that knee extensors are more prone to changes in activation when compared to knee flexors.

In this analysis, a methodology for calibrating an ankle join exoskeleton was presented, showing how optimal stiffness and elastic band rest length can be determined to minimize overall muscle activation during gait. Regarding optimal stiffness, there appears to be a threshold beyond which the impact of the exoskeleton becomes significant. In the case of the ideal model, effects became more noticeable when going beyond the 250kNm stiffens value. This is probably because a minimum stiffness value is required for the elastic band to generate any meaningful force that reduces other muscle groups' activation. On the other hand, elastic band rest length has a more significant effect on the activation of the different muscle groups. It is important to point out that when varying elastic band rest length, there exists a value beyond which the exoskeleton becomes trivial. This is because the rest length of the elastic band is long enough to not suffer any elongation during gait. Nonetheless, one must be equally careful when shortening the elastic bands' rest length as a minimal value can easily over-activate the dorsiflexors, resulting in an exoskeleton that does more harm than good.

Moreover, this analysis proposed the development of a realistic exoskeleton. Like this, an external noninvasive exoskeleton was presented, and its optimal elastic band stiffness, and rest length were determined. While the external exoskeleton held some resemblance to the ideal model, its location decreased the optimal stiffness value. This is probably due to its further distance from the ankle joint, allowing it to generate greater torque without the need of increased stiffness. Regarding the elastic band rest length, this was longer than the ideal model due to its new geometry and location, linking with the body just above and below the top and bottom links of the soleus.

Finally, the long-term effect of an extension spring ankle joint exoskeleton is a topic that requires further research. Using an exoskeleton for prolonged periods could result in an atrophy or deformation of the muscle groups. Since the exoskeleton compensates for some of the force required for terminal stance, muscles would become under activated, resulting in less exercise than usual, and therefore worsening their performance in the long term. However, this can be counteracted by performing muscle activity for extended periods of time (compared to exercise times without the exoskeleton), nonetheless, this trade-off is subject of its own analysis.

V. REFERENCES

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