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Passive Exotendon Spring Elements can replace Muscle Torque during Gait

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Abstract— **Nowadays, exoskeletons are widely used as assistive tools during gait rehabilitation, implementing strategies such as gravity compensation and metabolic cost reduction. However, these devices often require the use of motors and controllers. Our research is driven by the need for a simple, inexpensive and customizable device, a passive exotendon able to provide a desired torque profile to multiple joints. In a simulation model study, we asked whether it was possible to use diagonal tension elements, which act mathematically as basis functions, in order to reproduce the torque field generated by a healthy person during walking. This would allow us to create a wearable exotendon system made of passive elastic elements able to deliver this torque field to the lower extremity of the patient during gait rehabilitation. Our results showed that it is indeed possible to create a passive torque field from elastic elements that approximates the muscular torque demand for the walking cycle. This represents a starting point for the design of a passive exotendon capable of providing assistive torques to patients with motor deficits, thus reducing the metabolic cost of walking.**

I. Introduction

Gait rehabilitation is a key step in the lives of patients survived a stroke or an injury, allowing them to recover, at least partially, the ability to perform activities of daily living. Nowadays, exoskeletons are widely used as assistive tools during rehabilitation. One assistive strategy for gait is gravity compensation, which aims at reducing the weight applied to the muscles during motion and is provided by systems as the one presented by Banala et al. [1]. Metabolic cost reduction is another target of such systems. By making spring mechanisms that store and return energy during the gait cycle, the active energy input from machines becomes minimal.

Energy minimization schemes have focused o making gait easier. One prominent example is the unpowered clutch-spring system has been shown to reduce the oxygen consumption during healthy gait by about 7% [2] and an unpowered exoskeleton has been shown to reduce the metabolic rate in running by about 8% [3]. More recent studies on metabolic cost reduction have been done using a passive exosuit with two biarticular variable stiffness elements to support balance control. The experimental results showed that the average metabolic rate of unassisted walking was reduced by about 4% in walking assistance [4].

Models that can explore the role of adding technology can reveal insights on how to simply and easily reduce the metabolic cost for human subjects [5]. Dynamic walking is an important aspect of simulation [6], however position or state-dependent torques may be the best method of control.

The study of human gait performed during the years has provided us with useful data regarding the moments of force applied at our joints during the gait cycle. The goal of our study was to take the values of these torques developed by healthy subjects as a reference, in order to design a completely passive device for the lower extremity able to provide these torques to the joints during gait rehabilitation, thus reducing the metabolic cost of walking.

Meanwhile, some of our recent research is driven by the need for a simple, inexpensive, and customizable device, able to provide a desired torque profile to multiple joints. A first realization of this idea was the MARIONET (Moment Arm Adjustment for Remote Induction of Net Effective Torque), a diagonal tension element able to exert a desired torque at any joint [7]. This device is based on the change of moment arm to control the generated torque: by moving the point of insertion of the elastic element at different positions with respect to the joint center of rotation, different torque fields can be generated. The MARIONET overcomes the need for a rigid skeleton, using the very anatomy of the human body as a rigid link: a prototype consisted of a pegboard fixated at the shoulder level to which an elastic element was attached, connecting the elbow (one-joint MARIONET) or the wrist (two-joints MARIONET).

By acknowledging that the MARIONET acts mathematically as a basis function, thanks to its inherent sinusoidal torque profile, we can think about stacking several MARIONETs in parallel in order to deliver any desired torque profile, given by the linear sum of the torques generated by each element. This idea finds its realization in the ExoNET (Exoskeletal Network for Elastic Torque). Even if a first design of the device was intended for the upper extremity, it has the potential to be used for the actuation of several joints, hence it could also be implemented for the lower extremity.

In this paper, we present the simulation model of a wearable, completely passive device made of elastic elements (i.e. ideal springs), which can deliver the muscular torque demand for the walking cycle to the joints of a patient who is undergoing gait rehabilitation. For this purpose, we used data such as hip angles, knee angles, hip moments of force and knee moments of force generated by healthy subjects during walking, taken from David Winter's book "Biomechanics and Motor Control of Human Movement" [8].

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This device could help in addressing problems affecting patients survived a stroke, such as stiff-knee gait (SKG), which results in a lack of adequate knee flexion during the swing phase of the gait cycle [9]. Our goal is that of build a user-friendly, customizable, safe and inexpensive device that overcomes the need for motors and controllers, capable of providing assistive torques to patients with motor deficits. The proposed ExoNET system has the potential to be a simple and customizable device, giving the therapist the ability to adjust the arrangement of the elastic elements and the moment arms to suit the different motor deficits of the patients.

II. Methods

A. Model Development

With our study we want to show that optimization can contribute to selecting the best arrangement of a system made of passive elastic elements to replace the torques exerted by the muscles during walking. The system described above is called ExoNET and is made by stacking several MARIONETs, passive elastic elements here considered as ideal springs. This way we are creating multidimensional springs that allow to generate any torque field. This device is articulated around three joints: the hip, the knee and the hip and knee combined.

The model of the ExoNET in its simplest configuration is made of only single linear elastic elements at each joint (Fig. 1). The first element (in blue) connects the hip to the knee, the second element (in green) connects the knee to the ankle and the third element (in orange) connects the ankle to the hip.

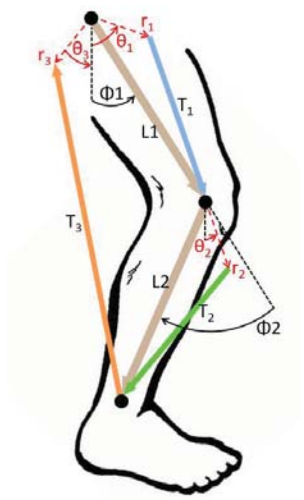

Figure 1. Schematic model of the ExoNET for the right leg. Each MARIONET exerts a pulling tension T represented as an arrow, blue for the hip MARIONET, green for the knee MARIONET and orange for the hip&knee MARIONET. L1 is the distance between the hip and the knee, L2 is the distance between the knee and the ankle, Φ1 is the angle between L1 and the vertical, Φ2 is the angle between L1 and L2, r is the distance between the Center of Rotation (CoR) and the point where the MARIONET is inserted, θ is the angle between r and the vertical.

In our model, each MARIONET is identified by three parameters: the distance between the Center of Rotation (CoR) and the point where the spring is inserted (r), the angle between r and the vertical (θ) and the resting length of the spring (L_0). Each elastic element is exerting a pulling tension (T) on the respective joint, whose magnitude is equal to the product of the spring stiffness and the displacement of the spring. In Fig. 2 we show the sign convention we used for the joint torques, where hip joint flexor moments and knee joint extensor moments are assigned positive signs.

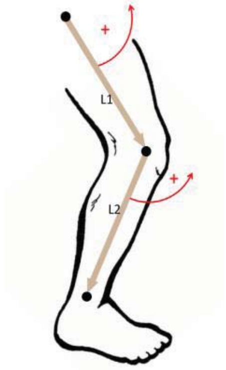

Figure 2. Sign convention for the joint torques. Flexor moments about the hip joint are positive moments, extensor moments about the knee joint are positive moments.

B. The Optimization Algorithm

The Matlab software was used to create a simulation model of the ExoNET and to implement an optimization algorithm able to find a set of optimal parameters (r, θ, L_0) for each elastic element, so that the ExoNET could approximate the desired torque field. In the first step, we set the anatomical parameters for the body. The lengths of the body segments, taken from anthropometric tables listed in David Winter's book, were referred to an average height of 1.70 m. Then, since the computational model was a simulation for a wearable device, we needed to set some constraints for the passive elastic elements forming the ExoNET. We modeled the MARIONETs as ideal springs and set a range of acceptable values for the distances between the Centers of Rotation (CoR) and the points where the springs were inserted (r), for the angles between r and the vertical (θ) and for the resting lengths of the springs (L_0).

C. The 'cost' function

Our optimization algorithm was based on the minimization of a defined 'cost' function, whose value was dependent on how much the estimated parameters (r, θ, L_0) differed from their acceptable ranges.

We implemented an optimization algorithm combined with the perturbation algorithm of Simulated Annealing, used to kick away the starting parameters of each optimization try from the optimal values found at the end of the previous try. This way we were sure that the final solution obtained was the best one and not one associated to a local minimum of the 'cost' function.

To start the optimization, the initial values of R, θ and L_0 were chosen as the mean of the respective ranges. During each optimization try, the minimization of the 'cost' function was performed by using the function 'fminsearch', contained on the Matlab Optimization Toolbox, able to solve nonlinear problems using a derivative-free method and used to find the sets of parameters (r, θ, L_0) corresponding to local minima of the 'cost' function. The repetition of the optimization for a preset number of tries, gave as a result the optimal parameters (r, θ, L_0) corresponding to the global minimum of the 'cost' function. These parameters were used to compute the torques created by the ExoNET, which were then compared to the desired ones.

The initial 'cost' was calculated as the sum of the squares of the residuals and the residuals were computed as the differences between the desired torques and the torques created by the ExoNET:

$$cost_0 = \sum_{i=1}^{n} (Desired\ Torque_i - ExoNET\ Torque_i)^2, \quad (1)$$

where *n* was the length of the *Desired Torque* matrix, whose first column contained the hip desired torques and whose second column contained the knee desired torques at each hip and knee angles combination.

For every parameter (r, θ, L_0), the initial 'cost' was increased by a *penalty*, given by the product of a positive constant (λ) and the absolute difference between the value of the parameter (p) and the upper bound (p_0) of its acceptable range (if the value of the parameter was higher than the maximum acceptable value) or the lower bound (p_0) of its acceptable range (if the value of the parameter was lower than the minimum acceptable value).

$$penalty = \lambda \mid p - p_0 \mid \quad (2)$$

Therefore, by summing Equations (1) and (2), the total 'cost' in each optimization try was equal to:

$$cost = cost_0 + \lambda \mid p - p_0 \mid. \quad (3)$$

D. The ExoNET Torque Field

By knowing that the torque vector (**τ**) is given by the cross product between the position vector of the point of application of the force (**r**) and the vector of the applied force (**F**),

$$\vec{\tau} = \vec{r} \times \vec{F}, \quad (4)$$

we were able to compute the torques generated by the elastic elements on the hip, on the knee and on the hip-knee joints, by using as **r** the distance between the CoR and the point where the spring was inserted and as **F** the tension exerted by the spring.

Considering the MARIONETs as ideal springs, the magnitude of the force (F) generated by each MARIONET could be computed through the Hooke's law as the product of the spring stiffness (k) and the displacement of the spring (L – L_0), where L_0 was the resting length of the spring.

$$F = -k\,(L - L_0) \quad (5)$$

Moreover, since the MARIONETs can be considered as basis functions, we obtained the total torque generated by the ExoNET by summing all the torques generated by each one of the *N* MARIONETs.

$$ExoNET\ Torques = \sum_{i=1}^{N} \tau_i \quad (6)$$

The result called *ExoNET Torques* was a two-columns matrix containing the generated torques for the hip (in the first column) and for the knee (in the second column) at each hip and knee angles combination.

III. Results and Discussion

A. Initialization of the Problem

Given that the outcome of the optimization algorithm was strongly dependent on the initialization of the problem, the first step was to find the optimal values for the stiffness of the springs and for the constraints of r, θ and L_0. The algorithm was executed several times in order to establish the ranges of the minimum and maximum acceptable values for the ExoNET parameters (r, θ, L_0).

Since our goal was to develop a device the least invasive as possible, we wanted the elastic elements to be inserted as close as possible to the joint, or even superimposed on the joint center of rotation. For this reason, we set the minimum value for the distances between the CoRs and the points where the springs were inserted (r) to 0.01 m and, in the 'cost' function, we penalized it in order to drive it to zero. Indeed, the contribution of an elastic element applied very close to the joint to the total torque generated by the device can be considered negligible and thus this elastic element may be removed from the device itself, making it lighter and more comfortable. Still for comfort reasons, r could not have high values, thus we did not accept values over 0.20 m.

For the resting lengths (L_0) of the springs we chose a range of values close to the lengths of the body segments, while for the angles θ we accepted all values ranging from -360° to 360°.

B. Gait Torques Field

Our optimization algorithm was implemented starting from the data provided by David Winter's book. In Fig. 3 we show the moments of force exerted by the muscles on the hip joint and on the knee joint during the gait cycle, at each combination of hip and knee angles.

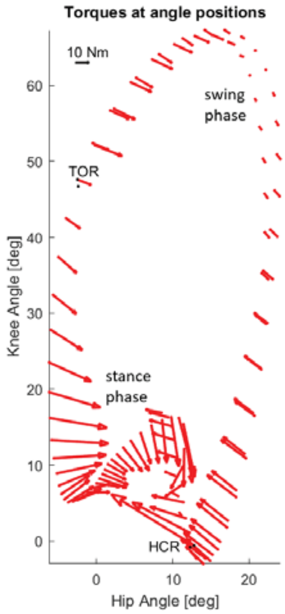

Figure 3. Average torque field produced by the muscles of the right leg of a healthy person during walking at each combination of hip and knee angles. The horizontal component of the red arrows is the hip moment of force and the vertical component is the knee moment of force. Hip and knee angles are referred to the vertical line. The points of TOR (Toe Off Right) and of HCR (Heel Contact Right) with the associated swing and stance phases are highlighted.

As we can see in Fig. 3, the torques needed during the stance phase are significantly higher with respect to the torques required during the swing phase. Our aim was trying to replicate such torques with our ExoNET device.

C. *One-element ExoNET System*

At first, we executed the optimization algorithm for an ExoNET system made of only one elastic element per joint. Since the maximum value reached by the torques exerted by the muscles was 54.4 Nm, we needed elastic elements with high stiffness to reproduce such values of torques in our simulation model.

We were able to identify an optimal arrangement of the ExoNET elements (Fig. 4). The points of insertion of the elastic elements resulted to be very close to the joints, suggesting that the wearable device with such an arrangement of the MARIONETs would be quite comfortable for the patient.

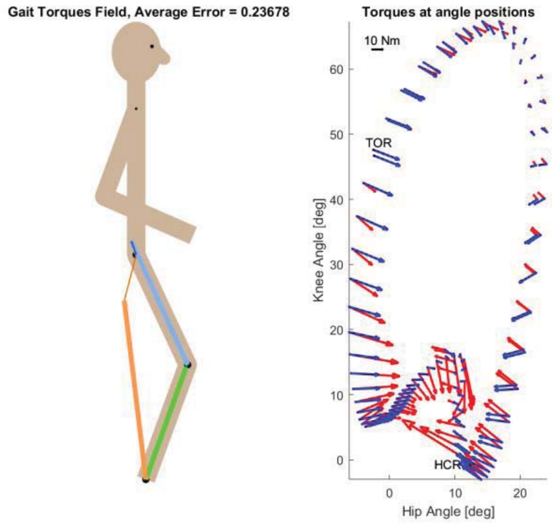

Figure 4. Arrangement of the one-element ExoNET system and associated torques generated by the device. To the left, a schematic of the body and the arrangement of the ExoNET, to the right, the torques created by the device (in blue) and the desired torques (in red). The joints (shoulder, hip, knee and ankle) are represented as black dots. Each MARIONET is represented as a line of a different color (blue, green and orange). The stiffness of the ideal springs was 2000 N/m.

The average difference between the torques generated by the ExoNET and the desired torques was about 0.237 Nm, that is a small percentage (0.44%) of the maximum value of torque exerted by the muscles (54.4 Nm). The higher difference between the ExoNET torque profile (in blue) and the gait torque profile (in red) occurs during the stance phase after the HCR, especially in the case of the knee joint (Fig. 5). This could be due to the sharp changes characterizing the muscle torque profile in this phase, which are hard to replicate with sinusoidal functions. Indeed, the torque field generated by the ExoNET was much smoother with respect to the one generated by a healthy leg.

Figure 5. Torque field produced by the right leg of a healthy person during walking (in red) and torque field generated by the one-element ExoNET system (in blue) with respect to the percentage of gait cycle. The points of TOR (Toe Off Right) and of HCR (Heel Contact Right) are highlighted.

D. *Two-elements ExoNET System*

In this case, the optimization was run for an ExoNET system made of two stacked elements per joint. Increasing the number of MARIONETs stacked together on the same joint allowed to decrease the stiffness of the elastic elements. In Fig. 6 we represent the best arrangement of the ExoNET found by the optimization algorithm. For some of the elastic elements, the points of insertion resulted to be farther from the joints, suggesting a bulkier appearance of the wearable device. Also in this case, the torques generated by the device in the phase right after the contact of the foot with the ground were lower with respect to the desired ones.

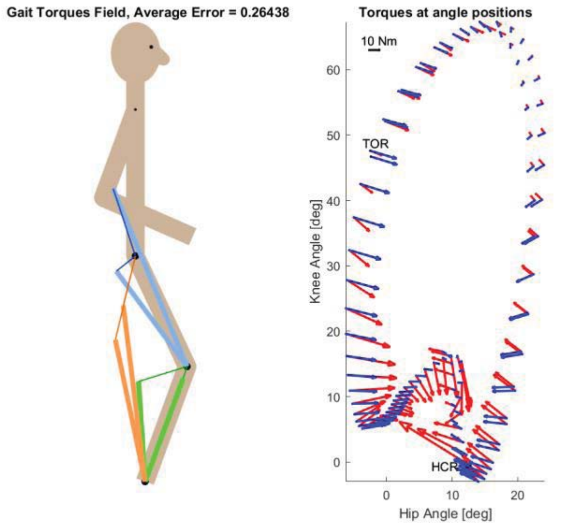

Figure 6. Arrangement of the two-elements ExoNET system and associated torques generated by the device. To the left, a schematic of the body and the arrangement of the ExoNET, to the right, the torques created by the device (in blue) and the desired torques (in red). The joints (shoulder, hip, knee and ankle) are represented as black dots. Each MARIONET is represented as a line of a different color (blue, green and orange). The stiffness of the ideal springs was 500 N/m.

E. Three-elements ExoNET System

By increasing the number of stacked elements per joint, the tendency of the elastic elements to move away their points of insertion from the joints increased. We can observe this in Fig. 7, where a three-elements ExoNET system is represented.

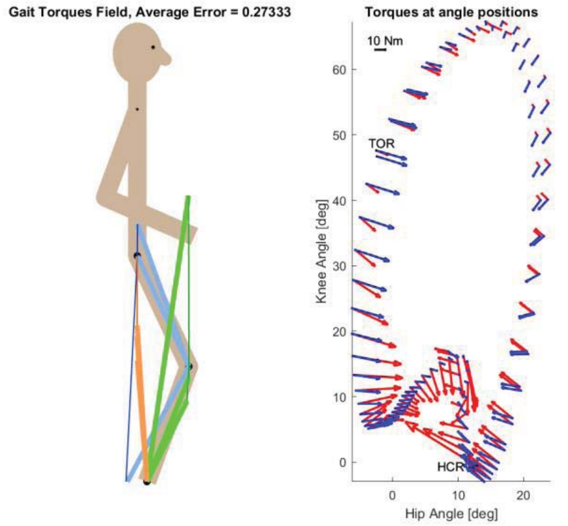

Figure 7. Arrangement of the three-elements ExoNET system and associated torques generated by the device. To the left, a schematic of the body and the arrangement of the ExoNET, to the right, the torques created by the device (in blue) and the desired torques (in red). The joints (shoulder, hip, knee and ankle) are represented as black dots. Each MARIONET is represented as a line of a different color (blue, green and orange). The stiffness of the ideal springs was 500 N/m.

F. Physical preliminary prototype of the ExoNET

In Fig. 8 we show a picture of a physical preliminary prototype of the ExoNET.

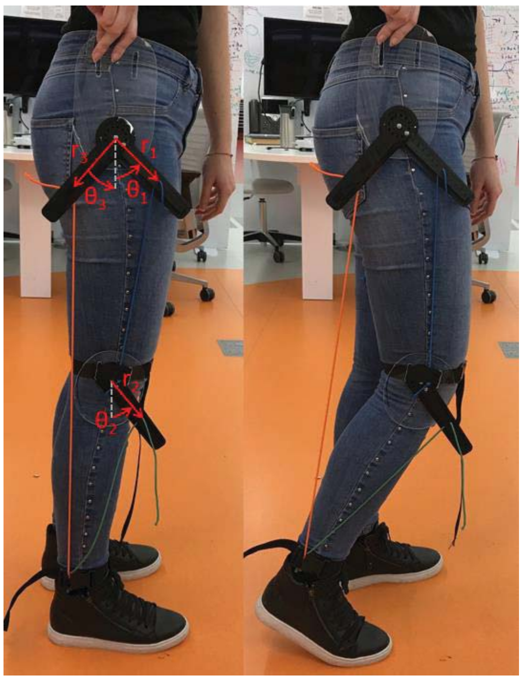

Figure 8. Physical non-functional prototype of the ExoNET. The parameters that can be adjusted on the ExoNET are indicated in red.

This prototype was built with very inexpensive materials, such as plexiglass and bungee cords, and it could be mounted on a belt thanks to the presence of two slots at the waist level. The need to adjust the moment arms of the elastic elements was addressed by using 3D printed rotators, to which the bungee cords were attached. Plexiglass plates were cut and shaped to form the rigid boards where the black rotators were inserted. The two plexiglass boards where assembled so that the CoRs of the rotators were approximately superimposed on the CoRs of the hip and knee joints. The black rotators were fixated to the plexiglass boards with screws and presented a series of equally spaced holes through which the bungee cords could be inserted. These rotators allow the tuning of the parameters r and θ, indeed, the distance between the CoR of the joint and the point where the spring is inserted (r) can be adjusted by inserting the bungee cord in different holes of the rotator and the angle between r and the vertical (θ) can be adjusted by rotating the rotators by 360°. Therefore, the optimal parameters (r, θ, L_0) returned by the optimization algorithm for each elastic element of the ExoNET can be used to arrange each rotator and each bungee cord accordingly.

This version shown is made of only one element per joint, but it is possible to add more elastic elements by stacking more rotators on the same plexiglass board. Moreover, for the realization of this prototype we used bungee cords, but we could also use elastic elements with higher stiffness, e.g. metal springs, which would also have a behavior more similar to ideal springs. The presented prototype was also not a functional for higher forces, and is shown merely to demonstrate geometry and that the ExoNET system can be implemented in a wearable device.

IV. Conclusion

The ExoNET is a multidimensional springs system. By using multidimensional springs that store and return energy during the gait cycle, the active energy input from the muscles decreases. This way, we can reduce the use of the muscles and thus we can reduce the metabolic cost of walking. Our results showed that it is possible to create a passive torque field from elastic elements that approximates the muscular torque demand for the walking cycle.

The simulated torque profiles generated by the ExoNET system suggest its potential for delivering assistive torques during gait rehabilitation. The fact that these torque fields showed limitations during the stance phase could be a disadvantage for some patient groups who need specific assistance during this phase, however, other deficits could be addressed, like the ones occurring during the swing phase, such as stiff-knee gait (SKG).

Our goal is that of build a user-friendly, customizable, safe and inexpensive device that overcomes the need for motors and controllers, capable of providing assistive torques to patients with motor deficits. The need for a customizable device comes from the fact that the desired torques for rehabilitation are different from patient to patient and they could also change with time as the patient recovers. The proposed ExoNET system has the potential to be easily arranged by therapists, but further investigations in a clinical setting would be needed to quantify the time required to perform the customization for each patient and for each stage of the recovery.

Next steps to further investigate the potentiality of this ExoNET system include the realization of a functional prototype of the ExoNET device to be tested on a treadmill in order to answer preliminary questions, such as: is the device comfortable to wear? Does it affect the gait? Do we have gait symmetry when wearing the device? Does it make gait easier?

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