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VIRTUAL REALITY APPLICATION FOR SQUAT EXERCISE WITH ROBOTIC EXOSKELETON

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Abstract. *With the increase in longevity due to advances in medicine and technology, the number of people with physical disabilities who look for therapy rises. Thus, in order to innovate the forms of therapy currently available, exercising games in virtual reality for rehabilitation purposes have been developed. These games are proven to be effective in bringing more engagement during practices, greater pain tolerance and many opportunities for innovation and customization, since the virtual reality environment carries an almost unlimited potential of activities and interactions. Therefore, given the progress in this field, this work explores ways to integrate a lower limbs exoskeleton with virtual reality. Herein, a virtual reality gaming exercising is proposed. While the virtual reality equipment provides visual feedback, the lower limbs exoskeleton will provide haptic assistance and feedback. The control architecture is described along with two use cases: movement assistance and exercising. The system is evaluated based on the user performance of the motor task inside virtual reality, such as time to complete the movement and total number of squats. This paper describes the system implementation and the results for one subject wearing the device, as a means of elucidate its functioning.*

Keywords: *Rehabilitation, Lower limbs, Exoskeleton, Virtual reality, Gaming, Haptic feedback, Squat*

1. INTRODUCTION

According to Max Roser and Ortiz-Ospina (2013), technological developments in the field of medical services dropped the mortality rates worldwide. At the same time, an increase in life expectancy contributed to social changes, increasing the number of elderly. The number of people today is almost twice as in 1975, despite the fact that the population growth rate has decreased in the last 50 years. In addition, in the year of 1975 the rate of people over 65 was about 7.7%, whereas in 2018 this number increased to 28.4%. In 2018, for the first time, the number of people over 65 years old passed the number of people under 5 years old. This shows a greater share of people who, as they grow older, are more susceptible to some illnesses and accidents. Ischemic heart diseases and cerebrovascular accidents (CVA, or strokes) have been the greatest causes of death around the world since 2003 and both can sometimes lead to impaired mobility of their victims (Ritchie and Roser, 2019; World Health Organization, 2020).

The World Health Organization (2004) states that there were about 15 million stroke victims in 2004. Among these, a third died, whereas a third continued to live without such serious consequences. However, 5 million stroke survivors were affected by some sort of disability resulted from the event. Stroke is the second leading cause of death around the world since 2003 and besides not being fatal, neurological impairments that engender motor weaknesses as a side effect are common among its survivors, which affect the practice of simple daily activities such as eating, walking, squatting and standing up. This statistic also includes ischemic strokes survivors, that are less fatal and account for 70% of the total cases (Goulart, 2016; Díaz *et al.*, 2011; World Health Organization, 2011).

These events altogether create an increasingly growing demand for health services, specially those dedicated to motor rehabilitation, defined as: “a set of interventions designed to optimize functioning and reduce disability in individuals with health conditions in interaction with their environment”. Today, 2.4 billion people around the world live a lifestyle that benefits from rehabilitation, which also includes people of other ages who have had their mobility affected for whatever reason (World Health Organization, 2020).

Conventional therapies can be exhausting and require a lot of financial resources, especially in respect to lower limbs, since taking care of a person usually requires the help of at least three physiotherapists or healthcare professionals to perform an exercise. This creates a high expense and limits access to services that still have a low reproducibility rate and end up being less intense. Thus, the integration of robots in this health field is an alternative that shows significant advantages when compared to traditional therapy (Huang, 2009). With this in mind, robots can replace the physical effort of specialized personnel, allowing for more intense and repetitive exercises. At the same time, robots facilitate access to

treatment and measure data that can be later used to evaluate objectively patient improvements.

1.1 State of the Art

Currently there is a wide field of research with several different types of exoskeletons focused on different goals and needs. Some deliver all necessary assistance in order help patients to walk again. Others are focused on different rehabilitation exercises, aimed for people who have partially lost their mobility (Díaz *et al.*, 2011; Chen *et al.*, 2016; Contreras-Vidal *et al.*, 2016). With the advances in this field of robotics, new ideas came up on how to restructure the current physical therapy practice to become more motivating. One of the ideas, applied on top of motivation theories, was the creation of virtual reality (VR) environments in conjunction with the rehabilitation exercises, so that the user is given a feeling of immersion in a world outside the everyday situations. Further, reward mechanisms are assigned to the exercises performed inside VR, to provide a sense of continuity and visualization of progress, which in turn guarantee to the participants in different studies a greater engagement in the activities (Kern *et al.*, 2019; Chen *et al.*, 2018; Howard, 2017; Soares *et al.*, 2020a; Tuah *et al.*, 2021; Soares *et al.*, 2020b).

To deliver a greater sense of reality to the virtual environment (VE), as well as a greater adaptability to the developed rehabilitation technologies so far, together with exoskeleton devices, there are methods to perform interaction between the forces exerted in VR and the forces exerted on the patient undergoing rehabilitation (Carignan *et al.*, 2009; Schiele *et al.*, 2006; Gupta and O'Malley, 2006).

This paper describes the design of a haptic interface for squatting with a lower limbs exoskeleton inside an immersive VR game, since both rehabilitation activities with exoskeleton and the application of VR in exercises have been shown to be tools with great potential to transform the current physiotherapy model and expand its accessibility. Section 2 describes the hardware, software and approaches employed. Emphasis is given to the control architecture, responsible for providing assistance or resisting to the user's movements through the exoskeleton robotic device. Section 3 summarizes the results of a validation test with one healthy subject only, followed by a discussion. Finally, section 4 draws some conclusions and points out limitations to be considered for future works.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Lower Limbs Exoskeleton: ExoTao

The ExoTao, Fig. 1 (c), was used for the project. It consists of a lower limbs exoskeleton developed by the Rehabilitation Robotics Laboratory from EESC-USP. It contains a total of six one-degree-of-freedom rotating joints, three for each leg. Each joint has an AksIM rotary encoder module to measure the user's hip, knee and ankle angle (dos Santos *et al.*, 2017). The ExoTao is actuated by means of a rotary Series Elastic Actuator (SEA) (dos Santos and Siqueira, 2019). The SEA consists of a direct current motor coupled with a gear system. Between the output of the gears and the robot, a customized elastic element is placed. This element of known-stiffness ensures compliant robot behavior, enables collocated torque control of the joint, as well as enhances safety during human and robot interaction. Here, only the right leg of the exoskeleton is used, and only the knee joint is actuated.

2.1.2 Virtual Reality Equipment: HTC Vive

The hardware being used for the user interaction inside VR is the HTC Vive, Fig. 1 (a) and (b), which consists of two handheld controllers and a head-mounted-display (HMD) to visualize the environment, respectively. The equipment also includes two lighthouse stations that are installed in the room. These stations track the controllers and HMD position in the physical world for the VR application.

2.1.3 Virtual Reality Development: Unity Engine

The immersive 3D virtual environment was developed using the Unity Engine (personal license), due to its active community and availability of game assets. The engine also has an embedded physics engine, which is used to simulate rigid body dynamics. All environment modeling was carried out using the free models from the Unity Assets Store. In addition, C# scripts were developed to define the behavior of variables in the VE, together with C++ scripts to handle the communication between the exoskeleton and the VR application.

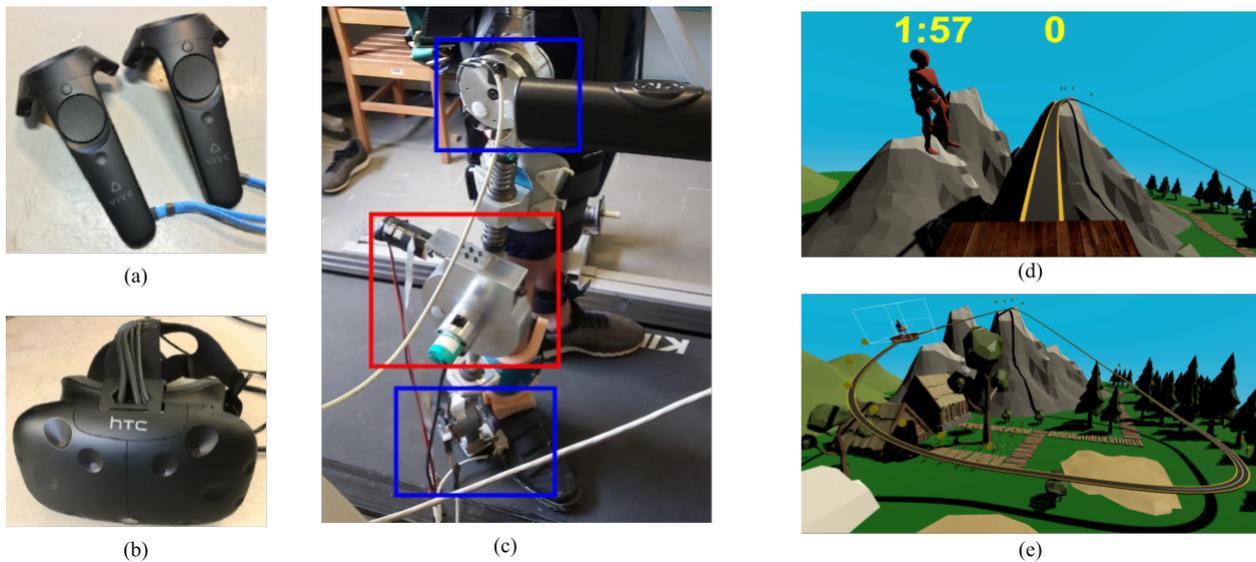


Figure 1. HTC Vive Equipment available on the laboratory, (a) handheld controllers, (b) head-mounted display. Lower limbs exoskeleton ExoTao, (blue) hip and ankle passive joints and (red) actuated knee joint (c). Instances of the VE seen behind the user (d) and from the Unity scene view (e).

2.2 Methods

2.2.1 Communication

In the setup there are two computers: one computer is connected to the robot and runs the controller, a C++ script; the second computer runs the VR application and is connected to the VR equipment.

The exoskeleton knee joint has one DC motor and two encoders connected to EPOS boards which, in turn, are connected to the first computer via Controller Area Network (CAN) ports. An Arduino Mega 2560 receives the data from the exoskeleton hip and ankle encoders via Serial Peripheral Interface (SPI) protocol, in which the microcontroller was set to master mode and the encoders were set to slave mode. The joint angles are obtained as 16-bit data packets and, as the microcontroller receives the data, it converts to degrees and transmits them to the first computer as a string via Universal Serial Bus (USB).

The computers exchange data through a wireless connection, based on a client-server architecture, already employed in former works from the research group (Villamizar *et al.*, 2020). In short, a server is run in the second computer; the VR application and the controller are clients and exchange data with one another through the server. By doing this, the exoskeleton encoder readings are sent to the VR, and the avatar can reproduce the exoskeleton movements; as the exoskeleton is attached to the user's limbs, they are tracked as well. The VR application also can send data to the control algorithm, but this is out of the scope of this paper. Here, only the knee joint angle displacement is transmitted from the first computer to the second one.

2.2.2 Creation of the 3D Virtual Environment

The development of the VE employed free assets provided by the Unity Asset¹ store. Many 3D object models such as trees, flowers, buildings and also C# scripts to define behavior and interactions among objects were employed from Unity Standard Assets. With these assets, a general scenario (RPG Poly Pack - Lite Asset) was built and a race track was generated, which the user will follow as he performs the squatting movement. The trajectory was generated by interpolating points using Bézier curves (Bézier Path Creator Asset).

Throughout the trajectory, collectible game objects will spawn. The number of collected objects defines the score of each round. The score implementation is supported by studies that state that scores and leaderboards can motivate and generate more engagement (Soares *et al.*, 2020a).

The avatar's position is restrained to the Bézier curve trajectory. In order to change its position, one must only provide at what point of the trajectory the user must go. This parameter varies from 0 to 1, where 0 refers to the start point of the curve and 1, the endpoint. If the provided parameter is greater than 1, it overflows so that the function is still within its limits.

The next position of the avatar is computed kinematically by means of an explicit Euler's method, as in:

¹<https://assetstore.unity.com/>

Algorithm 1: How the knee joint velocity, the slope and the velocity variables are related inside VR.

Result: Calculates the new position of the player based on the knee joint velocity $\dot{\theta}$ and the slope s ahead
 Initialization of all variables;
while *Game Running* **do**
 Receives knee joint angle θ from sensors;
 Computes $\dot{\theta}$ and slope s ;
 if $\dot{\theta} < 0$ **then**
 if $s > s_{th}$ **then**
 $v = v_{\theta} - r$;
 else if $s < -s_{th}$ **then**
 $v = v_{\theta} + r$;
 else
 $v = v_{\theta}$
 end
 end
 Computes the next player position x_p^{k+1} ;
 Updates player position along Bézier curve;
end

$$x_p^{k+1} = x_p^k + v\Delta t, \quad (1)$$

where the subscript p denotes the coordinates of the player at the k^{th} instant of time (or frame), Δt denotes the time between frames, and v is the avatar's linear velocity computed as being proportional to the knee joint velocity of the user, $\dot{\theta}$ multiplied by a constant referred to as speed factor α , as in $v = \alpha\dot{\theta}$.

Throughout the trajectory, there are different slopes. By means of C# scripting the slope, s , is calculated, compared against a slope threshold (s_{th}), and the player will be pushed forward more or less according to the magnitude of this slope, computed as:

$$s = \frac{y_c(x_p + h) - y_c(x_p)}{h}, \quad (2)$$

where the subscript c denotes the coordinates of the Bézier curve path. That is, before the player and the avatar move, the height of the Bézier curve a small step h ahead is computed, compared with the height of the Bézier curve at the current avatar position, and divided by the step. The slope will be negative if a decline is ahead, or positive in the case an ascent is present. A threshold value of $s_{th} = \pm 0.4$ is used. Slope values that fall within the boundaries of this threshold are considered as a flat path. Slopes that fall outside this interval will affect the velocity of the avatar. The velocity decreases in the case of positive slopes and increases if the slope is negative. For the time being, this increase or decrease is of same magnitude for both cases, and is referred to as a resistance factor, r . Algorithm 1 illustrates the procedure.

A reward system was also implemented in the VE, which allows to define a score, which comprises a strong motivational factor for the activity. Thus, coins were distributed along some regions of the track, which are collectible items for each time you pass on them and thus serve well as a measure of how far the user was able to squat along the way. Another feature was movement visualization, also important for good engagement as the user has some form of feedback about the movement being performed. Both the user's current score and the total test time were displayed to the user, in order to engage the users to perform more movements as fast as they can.

2.2.3 Squat Exercise

The squat exercise is an exercise performed in-place, consisting of two phases: downward and upward, in which the user lowers their hips and lifts them, respectively. During the downward phase, the user flexes the hip and the knee, whereas the ankle performs dorsiflexion. During the upward phase, the hip and the knee extend and the knee performs plantarflexion. The range of motion of the joints will vary for each person, but usually the deeper the squat, the greater the muscle activation (Jaberzadeh *et al.*, 2016). For control purposes, the standing position is calibrated as the reference value for measuring the joints displacements. Thus, this reference is also taken as the desired position to be achieved during the upward phase of the squat movement.

2.2.4 Control Architecture

The interaction force between the user and the robot is sensed through the spring of known stiffness of the SEA, K_{SEA} , according to Hooke's Law,

$$\tau_{int} = K_{SEA}(\theta_m - \theta), \quad (3)$$

where θ_m denotes the geared motor angle and θ the robot joint angle, i.e., the knee joint displacement of the user, since the robot is attached to his limbs. A torque control loop drives this interaction torque to zero by means of a PI controller. By doing this, the robot follows, to a certain extent, the user movements. The error of the torque controller is given by:

$$e_\tau = \tau_r - \tau_{int}. \quad (4)$$

When assistance is needed to return to the standing position, an outer impedance loop generates a reference torque, τ_r , so that the robot drives the knee joint of the user, θ to the reference value θ_r , which is zero, according to the following equation:

$$\tau_r = K_{imp}(\theta_r - \theta) - B_{imp}\dot{\theta}, \quad (5)$$

where K_{imp} and B_{imp} denote the virtual stiffness and damping, i.e., impedance, to be rendered. The greater these values, the closer the robot joint, thus the user joint, θ , approaches the reference trajectory, θ_r . This control architecture has been used in many works from the EESC-USP Rehabilitation Robotics Laboratory.

Assistance is achieved if $K_{imp} > 0$ and $B_{imp} = 0$; resistance is achieved if $K_{imp} = 0$ Nm/rad and $B_{imp} > 0$ Nms/rad. It is worth noting that the range of possible virtual stiffness is somewhat wide, from zero to the SEA stiffness value. On the other hand, the values of virtual damping fall within a small range, between zero and 5 Nms/rad, found empirically. The ideal impedance parameters for the squatting exercising depend on whether assistance or resistance to the movement is desired. Here, the damping parameter is set to zero, and the stiffness is varied, thus resistance is not delivered deliberately, only assistance. The control algorithm identifies that the user is standing up by analyzing the signal of the knee joint velocity, which has different signs whether the user is going down or standing up.

For this application, the robot will not provide any sort of assistance nor resistance during the downward phase of the squat movement, i.e., the impedance parameters are set to zero. During the upward phase, the virtual impedance parameters change, specifically the virtual stiffness parameter. A function $f(\dot{\theta})$ models this behavior, which consists of a first order system whose discrete form is given by:

$$K_{imp}^{k+1} = \beta K_r^{k+1} f(\dot{\theta}) + (1 - \beta) K_{imp}^k \quad (6)$$

where the reference value K_r is constant and multiplied by a piece-wise constant function, i.e., a Heaviside step, with the following conditions:

$$f(\dot{\theta}) = u(\dot{\theta}) = \begin{cases} 1 & \text{if } \dot{\theta} < 0, \text{ i.e., upward movement,} \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

The β parameter also changes slightly whether the user is standing up or going down (in Eq. 6 the dependence was suppressed for readability). It assumes the value of 0.01 and 0.02, respectively. The greater β , the faster the reference value is reached. When the user is standing, it is desirable that assistance takes place smoothly. On the other hand, when the user goes down, assistance is not desirable, since it would prevent the user from squatting.

2.3 Tests

In order to tune the controller, a first set of tests was performed with varying levels of assistance. A male healthy subject, with no physical disabilities (22 years, 74 kg, 1.76m) wore the lower limbs exoskeleton and performed a series of squat exercises from one to two minutes, with different levels of assistance, i.e., virtual spring stiffness values. The tests were repeated until a comfortable virtual stiffness value was found empirically. Stiffness between 20–50 Nm/rad were found to be suitable. The reference value was set to $K_r = 50$ Nm/rad.

Figure 2 shows the subject wearing the lower limbs exoskeleton performing the squat exercise. During the downward phase, the robot is under low-impedance control, i.e., impedance gains are zero, the robot follows the movements of the user, in order to drive the interaction torque between user and robot to zero. The not-shaded area denotes the upward movement, during which the robot assistance takes place.

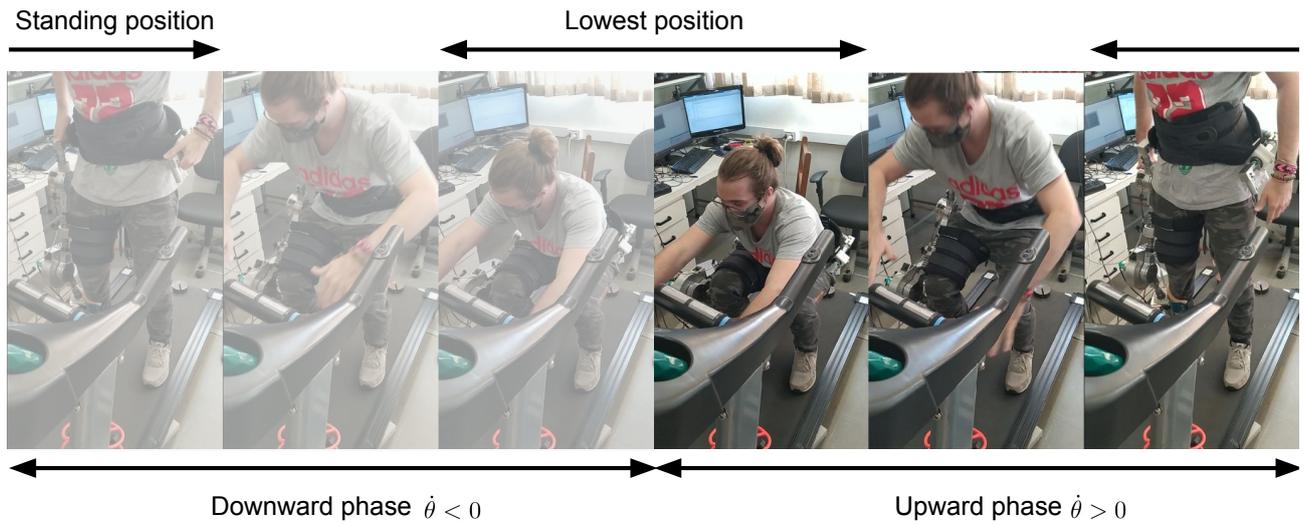


Figure 2. Subject performing the squat movement. The shaded area denotes the downward movement phase, during which there is no robot assistance. The robot assistance takes place in the upward phase.

3. RESULTS AND DISCUSSION

Figure 3 shows at the top the knee position (solid line) and velocity (dotted line) for a series of squats performed by the subject. At the bottom, it can be seen that the virtual stiffness values (dashed line) follows the reference stiffness value (thin solid line) as a first-order system. Non-zero stiffness values generate a reference torque (thick solid line) calculated by Eq. 5. The shaded area denotes the standing phase of the squat movement, i.e., when the angular velocity is positive. The shaded regions are also denoted by numeric indices from 1–5 for further reference to the region under analysis.

Within the time interval depicted by Fig. 3, it can be noted that five squats were detected by the control algorithm, as there are five shaded regions denoting the standing up movement of the exercise. The subject's knee angle performs a trajectory within -20 and -90 deg (i.e., a range of 70 deg), with a period of approximately 4 s, a considerably low frequency, since the subject was performing squats slowly. Mohr *et al.* (2018) performed measurements of the knee angle during the squat movement and obtained a similar period of 3 s and movement range around 70 deg. Their knee angle profiles have more narrow peaks. The peaks depicted in Fig. 3 are somewhat flat because the subject waited a bit before squatting again. To compare the results, please refer to Fig. 4, taken from Mohr *et al.* (2018).

The bottom figure shows the values of reference torque computed by the control law, as well as the values of reference and current virtual stiffness, which here were set to 50 Nm/rad/s. Lower values of stiffness were not delivering satisfactory assistance, according to the subject. Also according to him, this value was comfortable.

To make the virtual stiffness follow a first-order system, as in Eq. 6, prevented spikes in the reference torque, Eq. 5, delivering a more stable robot behavior.

If the first-order system behavior is removed, by assigning $\beta = 0$, spikes would be present whenever the user started the upward phase of the squat movement. When the values of stiffness are relatively small ($K_{imp} < 20$ Nm/rad), these spikes do not affect the robot behavior considerably. However, when the stiffness increases, these spikes lead to unstable behavior, and limits the assistance that can be provided.

The instability occurs due to the fact that the error component of the inner-torque control loop is also affected by the spikes. The reference torque, τ_r , propagates the spikes to the error, according to Eq. 4. Hence, the torque controller has to deal with an error signal which is suddenly too large, and saturates. In the same fashion, the reference torque component of the error goes suddenly to zero when the downward movement starts again. Though with less magnitude, this also contributes for an undesired robot movements. This oscillating behavior in general caused the robot either to move or stop suddenly, which yielded not only discomfort but also a greater occurrence of false detections of upward phases.

Though the first-order system approach solved this problem, as the user reaches the upward position, there is a chance that the robot is disturbed and starts to go on the opposite direction, moments before the user is once again standing. This can be seen in the second squat of Fig. 3. This is caused by non-ideal coupling of the robot and the human. The robot reaches the standing position a few seconds before the human stands up completely. When the robot reaches the final position and senses that the human is still moving, the velocity measurements are disturbed, and causes the described phenomenon. One way of prevent this from happening would be to measure the human velocity, rather than the robot, since the coupling is not ideal in practice. To acquire velocity measurements from inertial measurement units (IMU) attached to the human limbs rather from the robot encoder may help to solve this issue.

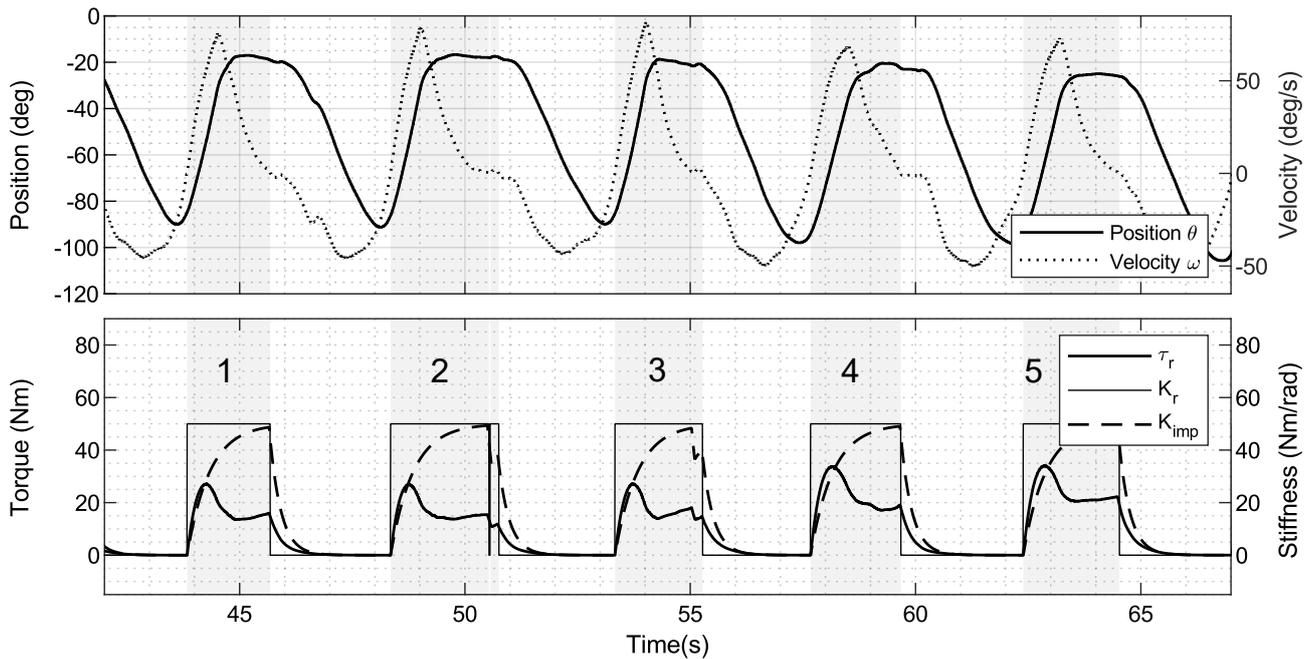


Figure 3. Tests with a healthy subject. (Top) knee position and velocity. (Bottom) Reference torque, reference virtual stiffness value and current virtual stiffness value. Stiffness follows a first-order system response subjected to a step, in order to prevent spikes in the robot behavior. Yet, spikes sometimes occur, as in the second squat.

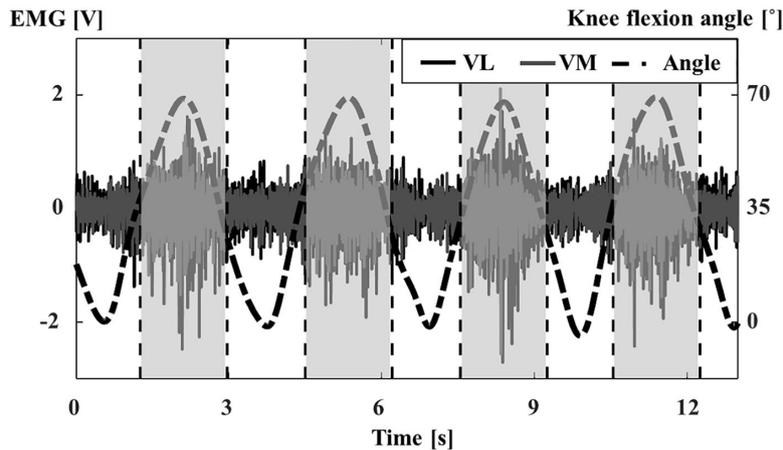


Figure 4. EMG and knee angle (Mohr *et al.* (2018)).

4. CONCLUSIONS AND FUTURE WORKS

For the time being, the lower limbs exoskeleton ExoTao was tested with a healthy subject, for the practice of the squat exercising with robot assistance inside an immersive VR application.

When the assistance was delivered during the upward phase of the squat movement, the robot showed to behave accordingly, i.e., the angle measurements are within the same range as the ones obtained from a squat without assistance (i.e., without the exoskeleton). It can be observed that the exoskeleton only exerted torque on the user's knee during the ascent movement, thus indicating the desired functioning. Moreover, the first order system used to drive the K_{imp} value to the reference value K_r also served its purpose, avoiding peaks at the beginning and end of the squatting. Still, peaks on the torque value τ_r can be observed right at the beginning of the upward phase, due to the large error distance from the squatting position to the standing position.

In summary, the controller architecture is suitable for this application, and the VR application delivers visual stimuli in order to generate user engagement.

To rely on the robot velocity to detect the upward and downward phases is not a very robust approach when the human and the robot are not tightly coupled. As the user exercised, the Velcro® straps loose themselves and end up compromising the coupling. The robot, then, reached the standing position before the user did and, since the human was still moving, the robot velocity measurements were disturbed, affecting the control algorithm and robot behavior.

These issues shall be addressed and new tests shall be performed with healthy subjects, in order to evaluate not only the haptic assistance delivered by the robot, but also the whole experience being delivered by the setup.

5. ETHICS APPROVAL

The tests were approved by the ethics committee of the University of São Paulo, Escola de Educação Física e Esporte de Ribeirão Preto, EEFERP-USP, CAAE (Certificado de Apresentação de Apreciação Ética) No. 41150620.7.0000.5659, decision statement (approval) No. 4.579.836. Participants were invited to take part voluntarily. All test data were stored anonymously. The participants were given the opportunity to withdraw their consent at any time as well as terminate their participation.

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