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A NOVEL MUSCULOSKELETAL-DRIVEN EXOSKELETON FRAMEWORK FOR SPINA BIFIDA REHABILITATION IN INFANTS

VICTOR A. HUAYAMAVE*, EMIR A. VELA†, WANGDO KIM†, TAMARA T. CHAMBERS*, ESTEBAN CENTENO†, AND BREANNA MACUMBER*†

* Department of Mechanical Engineering
Embry-Riddle Aeronautical University
Daytona Beach, Florida 32114, United States
e-mail: huayamav@erau.edu

† Department of Mechanical Engineering - UTEC
Universidad de Ingenieria y Tecnologia
Barranco 15063, Lima, Perú

†Department of Chemistry
University of South Florida
Tampa, Florida 33620, United States

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Abstract. Soft exoskeletons are lightweight robotic devices currently used for physical therapy and rehabilitation. Most of the current research on soft exoskeletons has focused on the adult population, providing limited options for infant physical therapy and rehabilitation. Spina bifida, a condition affecting the infant's brain and spinal cord, requires muscle movement treatment through physical therapy. Coupling physiological infant movement with soft robotics can provide solutions for rehabilitation and physical therapy. This study couples joint kinematics from a novel musculoskeletal model with a soft-robotic exoskeleton that uses vacuum-powered artificial muscles. The accuracy of the exoskeleton is assessed when replicating physiological infant kicks. Knee joint kinematics from the musculoskeletal model during infant movement were used to drive the soft exoskeleton. Preliminary results showed that the robotic system replicated infant kicks with lower frequency and small ranges of motion (RMS < 2 degrees) more accurately than those with higher frequency and large ranges of motion (RMS > 6 degrees). The proposed framework has the potential to replicate physiological infant kicks that could be used for infant physical therapy and rehabilitation.

1 INTRODUCTION

Spina bifida is a type of neural tube defect and occurs in approximately 1 per 1,000 births worldwide [1]. The neural tube is the structure that eventually develops into the infant's brain and spinal cord. This neural tube defect affects the nervous system and can lead to problems such as weakness or total leg paralysis. Treatment requires physical therapy and rehabilitation.

Robotic driven exoskeletons are used for rehabilitation to train muscle movement and assist in injury recovery. While the demand for these robotic rehabilitation devices has significantly increased, most have been developed for the adult population due to the increasing number of disabled and aged people [2]. In recent years, novel approaches have been used to develop assistive exoskeletons for walking children affected by cerebral palsy and spina bifida [3, 4]. However, there have not been any significant advancements in exoskeletons for the infant population. Spina bifida leads to motor dysfunction reducing mobility in infants. High physical activity has been recommended for rehabilitation. The proposed framework aims to couple the joint kinematics from a novel musculoskeletal infant model with a robotic exoskeleton that uses vacuum-powered artificial muscles. The purpose of this study is to investigate the accuracy of the previously developed robotic system when replicating physiological random and high frequency infant kicks. The proposed framework has the potential to advance the infant rehabilitation field and can be adapted to meet the needs of infants affected by spina bifida and other developmental conditions.

2 METHODS

For this study, an infant musculoskeletal model was coupled with a robotic system. Infant knee kinematics, obtained from a previously developed musculoskeletal model [5], were used as an input to drive a knee exoskeleton and to assess the accuracy of the exoskeleton's output. The general workflow for the proposed framework is shown in Figure 1.

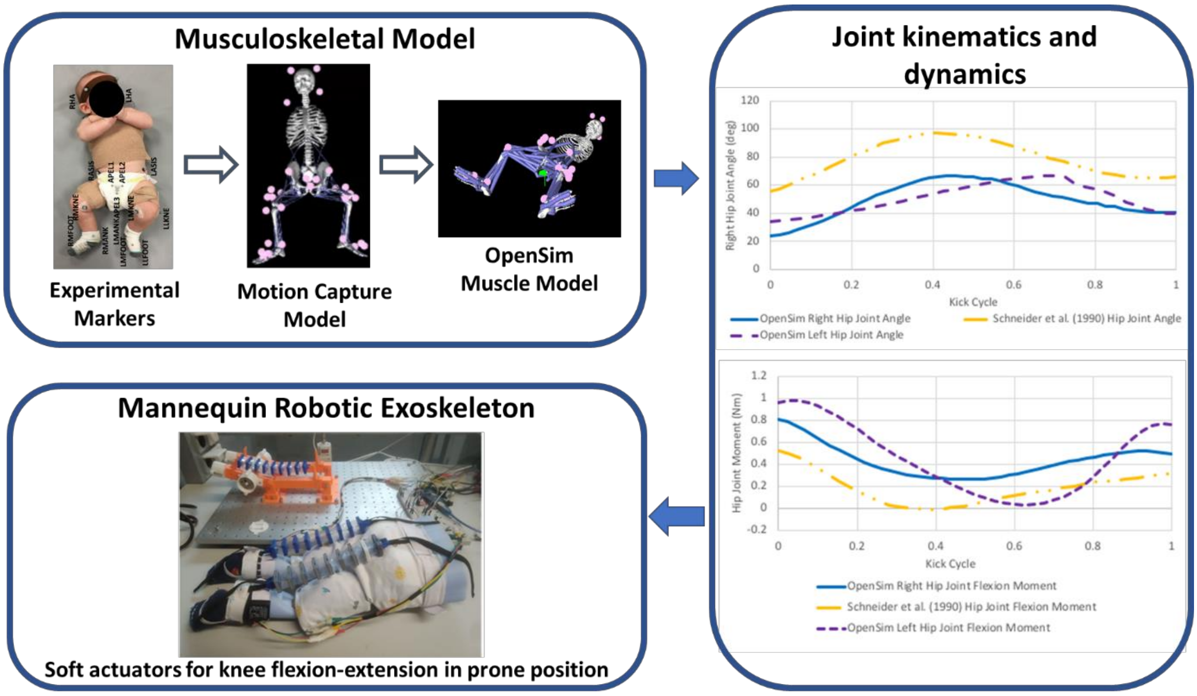

Figure 1: Coupled infant musculoskeletal computational model and robotic exoskeleton framework concept.

The musculoskeletal model used in this study was developed by scaling an adult model using experimental motion capture data from an infant. The infant exoskeleton system utilized in this study was comprised of knee joint controls that used soft pneumatic artificial muscles to perform cycles of knee flexion and extension. This robotic system was previously developed for infant physical therapies and has worked well with controlled sinusoidal trajectories, which are typical for infant physical therapy and rehabilitation [6]. The exoskeleton consisted of a soft vacuum-powered pneumatic artificial muscle actuator. Bench testing was performed using a developed infant mannequin that matched the anthropometric measurements of a 6-month-old infant. For the musculoskeletal model, inverse kinematics was used to estimate joint angles. The averaged kinematics from the infant musculoskeletal model was then used as an input to drive the exoskeleton joint controls.

2.1 Musculoskeletal model

The musculoskeletal model was derived using OpenSim [4] to quantify infant biomechanical parameters that are difficult to measure experimentally. Motion capture technology was used to capture the spontaneous kicking without any external stimulation. The experimental motion capture data for the infant musculoskeletal model was obtained following an institutionally previously approved IRB [7, 8]. Data was collected from a healthy, full-term male infant who was 2.4 months old lying in the supine position. The previously developed infant model used anthropometric measurements to scale the generic adult model [6]. Inverse kinematics was then used to estimate hip joint angles by solving a least squares optimization problem minimizing the distance between experimental markers and the corresponding model markers. The optimization used during scaling was a weighted least squares optimization problem given by Equation (1) [9, 10], where $\boldsymbol{q}$ is the vector of generalized coordinates being solved for, $\boldsymbol{x_i^{exp}}$ is the experimental position of marker $\boldsymbol{i}$, $\boldsymbol{x_i(q)}$ is the position of the corresponding model marker (which depends on the coordinate values), and $\boldsymbol{q_j^{exp}}$ is the experimental value for coordinate $\boldsymbol{j}$. Prescribed coordinates are set to their experimental values. The goal of the optimization problem was to place the model markers in the position that closely matched the subject's position while minimizing marker error.

$$\min_{q}\left[\sum_{i \in \text{markers}} w_i \left\|x_i^{exp} - x_i(q)\right\|^2 + \sum_{i \in \text{unprescribed coords}} w_j \left(q_j^{exp} - q_j\right)^2\right] \tag{1}$$

$$q_j = q_j^{exp} \text{ for all prescribed coordinates } j$$

The infant knee kinematics from the random kicking motion were obtained from the musculoskeletal model for 42.89 seconds, as shown in Figure 2. A total of 5 kicks (A, B, C, D, and E) were selected, and the selection was based on range, transient response, and stable response. Kicks were sought with a movement amplitude of at least 5°. Smooth transient response kicks were kicks that did not display oscillations or abrupt changes during flexion, and stable response kicks were kicks that remained stable after reaching the maximum angle during the kick cycle. However, kick E was discarded because the system was not able to achieve the desired angle in the given small time interval (0.2 seconds). Each kick exhibited extension, maximum flexion, and extension again as the infant kicked freely. These specific kicks from the musculoskeletal model provided the knee range of motion to be used as the input for the vacuum powered artificial muscle to assess its accuracy when replicating physiological infant kicks.

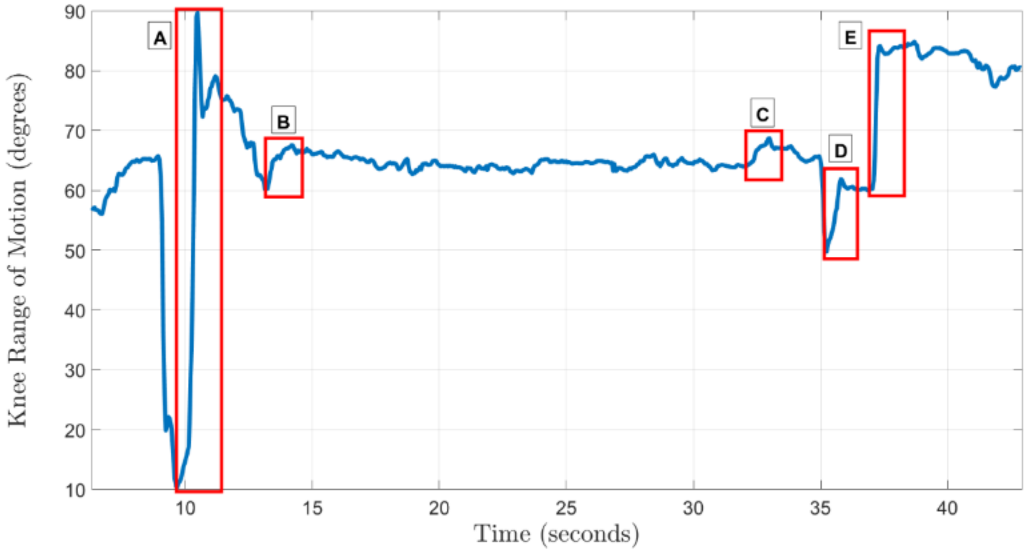

Figure 2. Physiological knee range of motion during infant movement from musculoskeletal model

2.2 Artificial Muscle Actuator

The robotic exoskeleton used a Vacuum-Powered Artificial Muscle (VPAM) [6]. The previous study utilized data on an infant during physical therapy to demonstrate the capabilities of the actuator. Results showed that the VPAM maintained successful exercise range of motion and smooth motions for the infant. The VPAM used a modular structure comprising of cells clipped in a collapsed state and unclipped when desired to account for infant growth. Clipping worked by sliding clips on the external ring and attaching two neighboring rings by deactivating the clipped cell. This allows the VPAM to adjust to its total contractile length. The VPAM was used due to its high forces and high contraction ratios and consisted of four components: a flexible membrane or skin, internal rings, external rings, and anchoring clips, as shown in Figure 3.

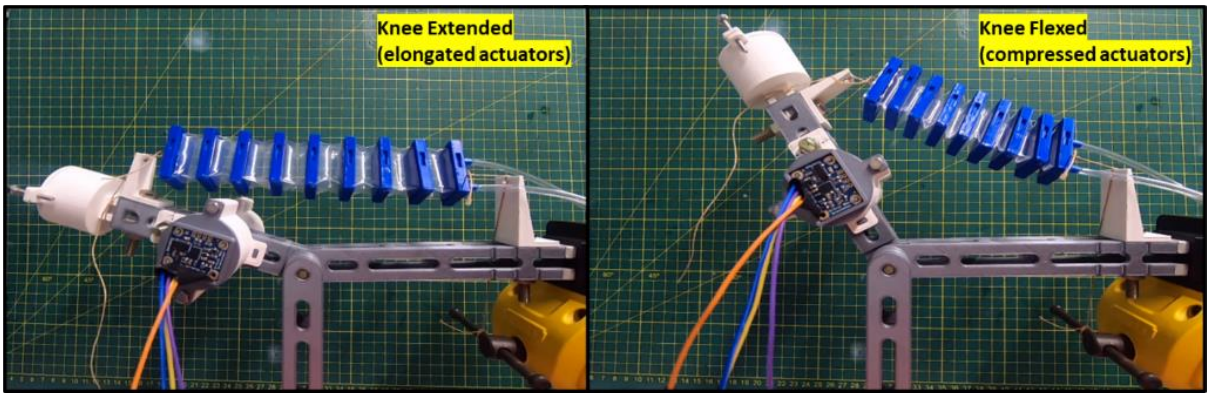

Figure 3. Exoskeleton robotic knee with vacuum-powered muscle bellow actuator.

The external rings allowed for the length-adjustable feature to be realized by clipping and unclipping the actuator cells. The artificial muscle works with vacuum pressure. When air is removed, the muscle contracts, and when air is added, the muscle relaxes. The actuator is attached across the knee joint, with anchoring locations along where the calf and thigh are located. Adhesive Velcro was used to attach one end of the actuator to the calf (where the IMU was placed to measure the flexion angle), while the other end was placed at the thigh. Fixing one end of the actuator to the thigh ensures that when the actuator is contracted by the pressure change, the leg is lifted due to the tensile force exerted on the calf. For the desired pressure, the actuator outputs a nonlinear tensile force. However, estimating the pressure needed to replicate specific ranges of motion is challenging due to the complex dynamics of the VPAM. Therefore, a Proportional-Integral-Derivative (PID) controller was used. A PID controller is a type of control algorithm that allows the control of a physical variable to follow a reference (or desired value) based on the sum of the error (measured value - desired value), the integral of the error, and the derivative of the error multiplied by gains K_p $(proportional\ gain)$, $K_i(integral\ gain)$ and K_d $(derivative\ gain)$. The PID used knee joint kinematics (obtained from IMU) as the input and the data from the musculoskeletal model as the reference. Then, the PID estimated the needed pressure for the desired knee range of motion. The controller gains used were (K_p = 0.4, K_i = 0.002, K_d = 0.02) and were tuned manually and experimentally.

3 RESULTS

The results showed that the system was able to smoothly follow the desired trajectory. However, there were differences between the measured ranges of motion for the robotic system (blue solid line) and the desired musculoskeletal model ranges of motion (blue dotted line), as shown in Figure 4.

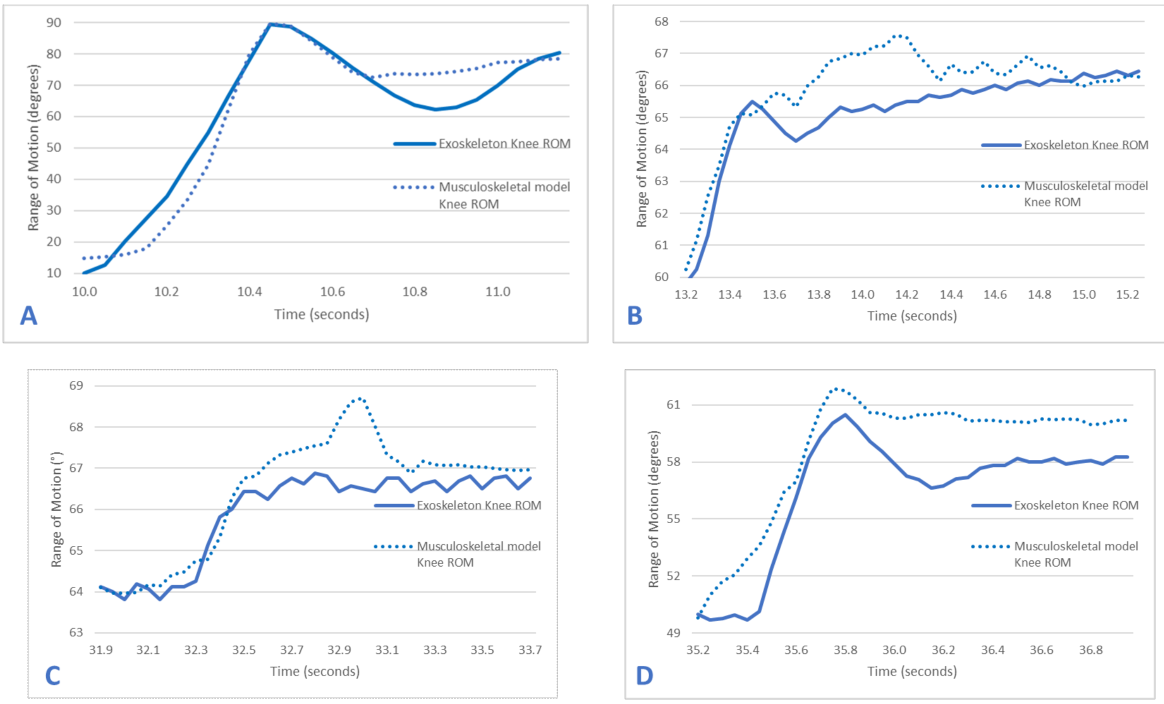

Figure 4. Comparison of experimental results between the musculoskeletal model and the soft-robotic exoskeleton system for all the selected kicks.

Table 1 shows the root mean square error (RMS) for each kick (A, B, C, D, E). Kick A has the greatest error compared to the other kicks, which was expected since this kick had the largest knee flexion range of motion (80 degrees). Additionally, there was a noticeable difference between the musculoskeletal model and the robotic system when initiating the movement. While the system followed a linear path, the musculoskeletal model's motion exhibited exponential behavior. The transient period was also complex to follow because these kicks happened quickly, between 0.2 and 0.4 seconds. The high speeds of the kicks were difficult to simulate with the current controller due to the limitations of the robotic system.

Table 1: Root mean square (RMS) error for each kick.

Kick	RMS (degrees)
A	6.67
B	1.06
C	0.76
D	2.34

While the robotic system was not able to precisely follow the infant knee kinematics during the transient period, it showed a significantly lower error when tracking the infant knee kinematics in the stable period (< 2°), as shown in Figure 4. The lower amplitude kicks had a smaller error because they did not require large velocities to reach the maximum flexion value. The results suggested that the system could perform movements that displayed similar behavior to the desired motions but were unable to replicate them perfectly due to the rapid speeds at which they occurred (<0.5 seconds). Further analysis and tuning of the current control algorithm (PID) will be completed in future iterations of the work to improve the reported errors.

4 CONCLUSIONS

Exoskeletons for therapy and rehabilitation have been developed focusing on the adult population while providing limited options for infant rehabilitation. This study aims to couple an infant musculoskeletal model with a soft-robotic system to replicate physiological infant kicks and assess the robotic system's accuracy simulating the random and high-frequency motion observed in infant kicks. The previously developed soft-robotic exoskeleton worked well with controlled ranges of motion and frequencies, which are typical of rehabilitation protocols for infants suffering from spina bifida. However, the random infant knee kinematics contained high-frequency kicks, and the exoskeleton was not able to accurately replicate all the investigated kicks.

The robotic system performed significantly better for kicks displaying small ranges of motion and frequencies. On the other hand, the system did not perform well with high ranges of motion and high frequency kicks, showing the largest RMS error (6.67 degrees). In addition, the robotic system currently works better for flexion because the extension is accomplished using only gravity, which greatly limits its performance. Future research will implement a passive component that can generate an additional return force. The proposed vacuum-powered artificial muscle design could be used in other applications outside the biomechanics field.

There were several limitations in this study. There was an age difference between subjects used to develop the musculoskeletal model and the soft-robotic system. The musculoskeletal model was based on the kinematics of a 2.4-month-old infant, and the exoskeleton was built using anthropometric data of a 6-month-old infant. Another limitation was that the infant musculoskeletal model represented an infant lying supine while the vacuum-powered robotic system represented an infant in the prone position. However, this did not affect the results because both cases behave like a simple pendulum with a revolute joint. Although the weight distribution is not the same, this was compensated by using the PID controller, which followed the given reference regardless of the difference in weights of the subjects.

The proposed framework has the potential to advance the infant rehabilitation field and can be adapted to meet the needs of infants affected by spina bifida and other developmental conditions. Our study also paves the way for the development of rehabilitation technologies using virtual reality.

ACKNOWELEDGMENTS

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