Toward Human Centered Generative Design: Model-based Assistive Device Design for a Simple Movement

THESIS

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By

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Abstract

Generative design (GD) is becoming a common method of product design, but little research has been applied directly to the problem of ergonomics and biomechanics in generative design (Urquhart et al., 2017). Recent advances in human factors engineering such as digital human modeling as well as predictive optimizations (Handford and Srinivasan, 2017) opens new frontiers for GD-based human centered design (Demirel, 2023). Current work in this research-area of generative design has not explored biomechanics-focused devices such as exoskeletons or similar assistive devices. Our overall goal is to explore possible methods of using generative design in conjunction with digital human modeling to design devices and tools that improve the work efficiency between the user and the tool. Specifically, in this study, we focused on building the framework for iterative exoskeleton component design for a squatting motion.

The original goal was to develop a larger scale generative design algorithm that could build multi member devices based on various input constraint and requirements, automatically evaluating multiple topological and parametric variations of the device. However, this project scope was simplified due to time constraints. Here, we considered

and optimized a single-member single-joint assistive device within a simulation framework built in MATLAB's simscape, laying the foundation for future work involving more complex topologies.

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To my friends, you have encouraged me more than you know. I would especially like to dedicate a moment to remember one of my dearest friends, Isaac Malphrus, who sadly is no longer with us. Isaac was a huge source of joy in my life that never failed to brighten my days, no matter how difficult. Though he is not here to see this day, his spirit, and the memories we created together continue to inspire joy in my life. I am forever grateful for the time we spent together and the impact he had on my life.

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Table of Contents

List of Figures

Chapter 1. Introduction

Current methods for designing consider ergonomics and human factors late in the design process which is inefficient (Demirel, 2023). A way of inserting human factors into the design process early is through generative design, and utilizing an iterative approach to find optimal designs that consider all relevant factors at once. Recent work has been done that explores this method, but these have been limited to a single structural member at a time and do not usually consider bio-mechanics principles (Urquhart et al. 2022a, Urquhart et al. 2022b, Demirel et al 2021). If an iterative model with generative design is formed with the ability to add multiple members with multiple different types of materials and properties, a more holistic structure could be designed. For example, if a designer seeks to develop an exoskeleton suit with multiple pieces that connect with movable joints utilizing generative design, they will need to specify constraints including the location of the joints and forces between the members. It would be advantageous for the generative design program to be able to change and find the optimal locations for these joints, as well as members that can stretch and conform to the body, or actuators that can exert forces or change properties (e.g., Material stiffness).

Designing complex exoskeletons by automatically generating devices with distinct topologies or configurations of the different device parts, then evaluating such device designs biomechanically with respect to functional requirements and biomechanical benefit, and then selecting an optimal device automatically, remains an open problem. Over the years, a number of exoskeletons have been built (Gull, Pesenti et al. 2022, Kermavnar et al. 2020) and are currently in use commercially, but these were designed using human understanding of the relevant task biomechanics and some analysis. Here, our goal is to perform a simplified version of this design process for a squat movement, such as would be used while lifting a heavy object, and using a simplified single-member single-joint exoskeleton morphology.

Significance

The test case of an exoskeleton for spinal support is important due to the need for methods to mitigate the high numbers of back injuries in many different occupations (Ramirez et al. 2022). Second, the continuation and expansion of recent research in the areas of ergonomics and biomechanics design, utilizing generative design to insert these principles early in the design process may produce better designs and less human iteration.

In the evolving field of biomechanical assistive devices, the integration of generative design (GD) and digital human modeling (DHM) presents significant potential yet remains underexplored. While assistive devices such as exoskeletons have shown promise in enhancing human capabilities and reducing chronic pain and injuries, current design methodologies often lack the customization and adaptability necessary to cater to the unique anatomical and biomechanical needs of individual users. The absence of a tailored approach in the design of these devices can lead to suboptimal performance. Furthermore, traditional design methods are often time-consuming, resource-intensive, and limited in their capacity to prototype designs iteratively and rapidly. Methods that address these challenges would be of great usefulness.

Objectives

This research aims to address the gap in utilizing GD and DHM for the design of biomechanical assistive devices. The objective is to explore new iterative approaches that can lead to a faster and cheaper design process and more personalized and adaptable designs, thereby pushing the boundaries of current practices in the development of biomechanical assistive devices.

The objectives had to be changed from what was originally planned due to time constraints. The end goal remained the same, but due to the complexity of the original objective, I was only able to address a simplified version and build a foundation to develop in future work. Thus, the revised **problem statement** is to build a framework to simulate human movement and evaluate exoskeleton designs for particular movements, focusing on the squat movement.

In the following chapters, we describe a human movement simulator built within MATLAB simscape, demonstrate its ability to perform a squat movement, evaluate the torques needed to produce the squat, and then design an optimal single-joint passive exoskeleton that minimizes some measure of effort.

Chapter 2. Methods

In order to build a human centered, iterative and generative design method, I had to determine a method of quantitatively evaluating each exoskeleton design within the proper context of the movement task. This needed to involve some method of simulating a human using each device. The simulation preferably needed to be fast without compromising accuracy too much. A few simulators were considered; these were “MUJOCO”, “Open Sim”, and “Simscape Multibody”. Each of these simulators have different benefits.

MUJOCO (Todorov et al, 2012) appears to be a great option due to its fast simulations and its “API” which allows you to integrate with other programs such as MATLAB. MUJOCO is also useful when simulating interactions between objects.

Open Sim also seemed to have great benefits due to its higher accuracy in human simulations and prebuilt models, especially involving detailed muscle models and properties. With this higher accuracy, typically comes a higher computational cost and slower simulations which would be a large downside when running many simulations however. After looking closely at the benefits of each of these simulators, it was decided that MATLAB Simscape was the best option to start with due to my familiarity with it and its related tools such as Simulink and MATLAB, its adequacy for the required task, and its easy communication with the rest of the MATLAB and Simulink framework, which allows for interacting with sophisticated optimization routines.

Human body model. I found the average dimensions of an adult human male as seen in figure 1 (Singh et al, 2016) and use these as reference to construct several segments of a human body that was constrained within a 2D plain. Each body segment was made as rectangular extrusions and include the feet, lower leg, upper leg, torso, upper arm, lower arm, hand, and head (figure 1, right panel). These were connected using revolute joints that were at the center of the ends of the rectangular segments and angle limits were set for the motion of the joints to approximately mimic that of a human. The arms and legs were combined such that there was one leg and one arm that was representative of each set of legs and arms. The average mass per body segment was found, as seen in figure 2 and the mass for each of the above segments was calculated based off of the total mass (de Leva, 1996). The foot was permanently constrained to be attached immovably to the floor in order to simplify the simulation.

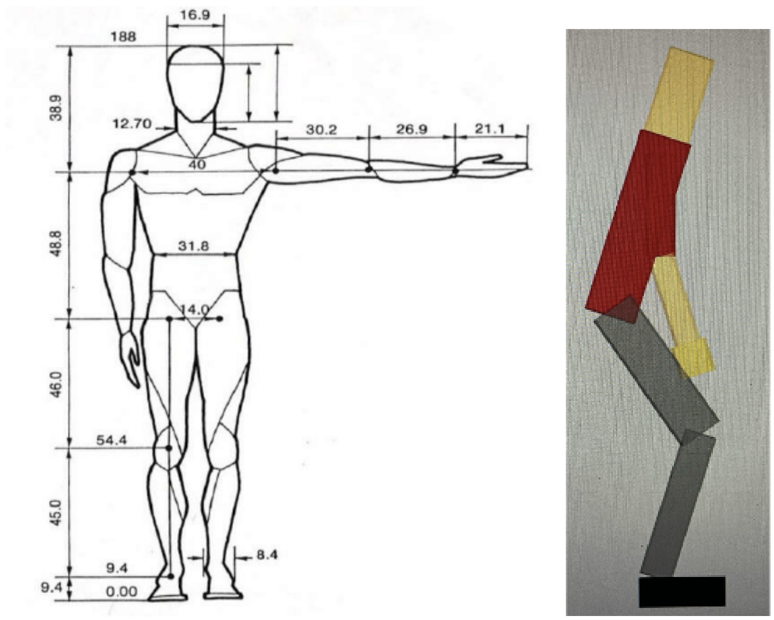

Figure 1 Left panel shows average dimensions of an adult human male (Singh et al, 2016). Right panel shows the model we built in simmechanics.

Segment	Male	Female
Head	8.26%	8.20%
Whole Trunk	55.1%	53.2%
Thorax	20.1%	17.0%
Abdomen	13.1%	12.2%
Pelvis	13.7%	16.0%
Total Arm	5.70%	4.97%
Upper Arm	3.25%	2.90%
Forearm	1.87%	1.57%
Hand	0.65%	0.50%
Forearm & Hand	2.52%	2.07%
Total Leg	16.7%	18.4%

Figure 2 Body mass percentage per body segment (de Leva, 1996)

Movement actuation and optimization. I decided to focus on a squatting motion because of its relatively static/ slow movement as well as the fact that its is a common task when bending down to pick something up and involves putting stress on the back, which is a common place for work injuries. Now that we knew the type of motion to address, we attempted two methods of actuating this motion. These methods were to:

1) specify the torque applied to each joint and automatically calculate the motion, and
2) specify the angular motion of each joint and automatically calculate the torque for each joint.

Approach 1: optimization using fmincon. I initially used the first method and specify the torque for each joint. This was done using a built-in function in MATLAB called "FMINCON". FMINCON allows you to optimize non-linear functions based on an objective function and several constraints. The objective function is a function that is defined by the user and has a single output that it attempts to minimize. It is known that humans naturally attempt to minimize "metabolic cost," or the amount of energy the body uses, when determining our motion so it was decided to use a representative metric for the energy cost. This was found by calculating the integral over the time interval of the absolute value of the torque (figure 3) for each joint that was required for the motion and then taking the sum of all of these over all the joints.

Objective function to be minimized:

- $\sum_{i=0}^{n} E_{cost,i}$

- $E_{cost} = \int_{t_0}^{t_f} |T(t)dt|$

- $T(t) = joint\ torque$

Constraints:

- $Y_{hip}(t = 0) = Y_{hip}(t = t_f)$

- $Y_{hip}\left(t = \frac{t_f}{2}\right) = Y_{hip,\,min}$

Figure 3 FMINCON objective function and constraints.

FMINCON also allows you to set constraints. In this case, we set coordinates that the "hip" had to move to at specific times. The hip had to be at a specified point below its starting point at the middle of the time interval and had to make it back to its starting coordinate at the end of the time interval. I hoped this would force the model to crouch down then back up using the least energy possible which would hopefully mimic a human "squatting" motion. This method ultimately failed to converge to the desired motion, however, it did display some interesting results. At one point, the model appeared to be converging to a motion where it leaned all the way forward for most of the time interval, but then swung its head and arms up in order to make it back up to the "standing" coordinate by the end of the interval. This appeared to be like a natural human motion, using the momentum of their extremities to propel themselves up off the ground. Although I believe this method could ultimately give the best and most natural results given more work, it was decided that this would take too much time for this study.

Approach 2: Fully prescribed motion. The second approach we tried method involved specifying the angular motion of the joints and automatically calculating the motion and the torques. First, I had to determine the correct angular motion of the joints that would result in a squatting motion. This would preferably be done using a motion capture system of an actual human squatting and then mapping the Simscape model to this motion. For simplicity, I used ChatGPT to give me a series of angles for each joint that would produce a squatting motion. I put these angles in my MATLAB script as a time series and made minor changes (figure 4) to produce a motion that closely resembles a person squatting down and then back up and I used this to actuate my model. The calculated torque for each joint throughout the time interval was then sent back from

Simscape. The energy used for this motion was found again using the same calculation as was done before (figure 3).

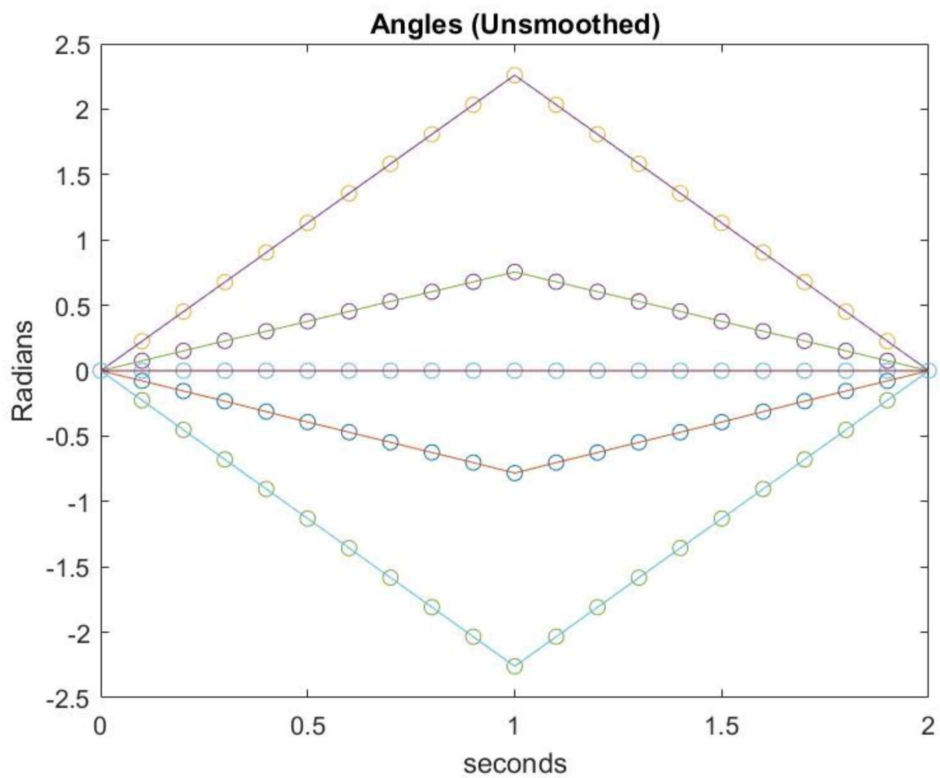

Figure 4 Unsmoothed joint angles.

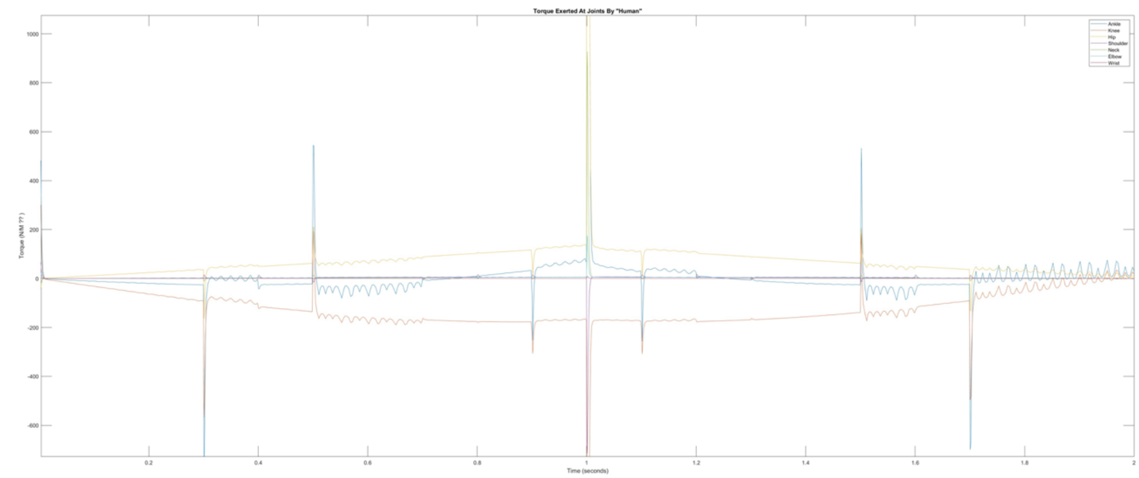

Figure 5 Joint torques for tracking the unsmoothed joint angles of Figure 4.

The joint torques (figure 5) from the unsmoothed joint angles displayed some large spikes that seem to correspond to quick changes in motion, such as when the model changed directions from squatting down to standing up as well as at the sudden start and stop at the beginning and end of the time intervals. This is due to the very large forces that would be required to change the momentum in order to produce the prescribed angular motion. As this seemed unnatural for a human being, in subsequent analyses, we smoothed the angular motion. I did this by using a MATLAB command called “lsqnonlin” which is a curve fitting function that allows you to set constraints. I wanted to fit a polynomial function to the joint angle data but make the transitions between movements less “sharp”. In order to do this, I set the constraints such that the first and second derivatives at the ends and middle of the functions would equal zero. This would ensure that the changes in momentum would not require such a large force. I also used this function to try out and visualize several different order polynomials, (figure 6) in order to determine which one seemed best, and I decided on a 7^{th} degree polynomial (figure 7).

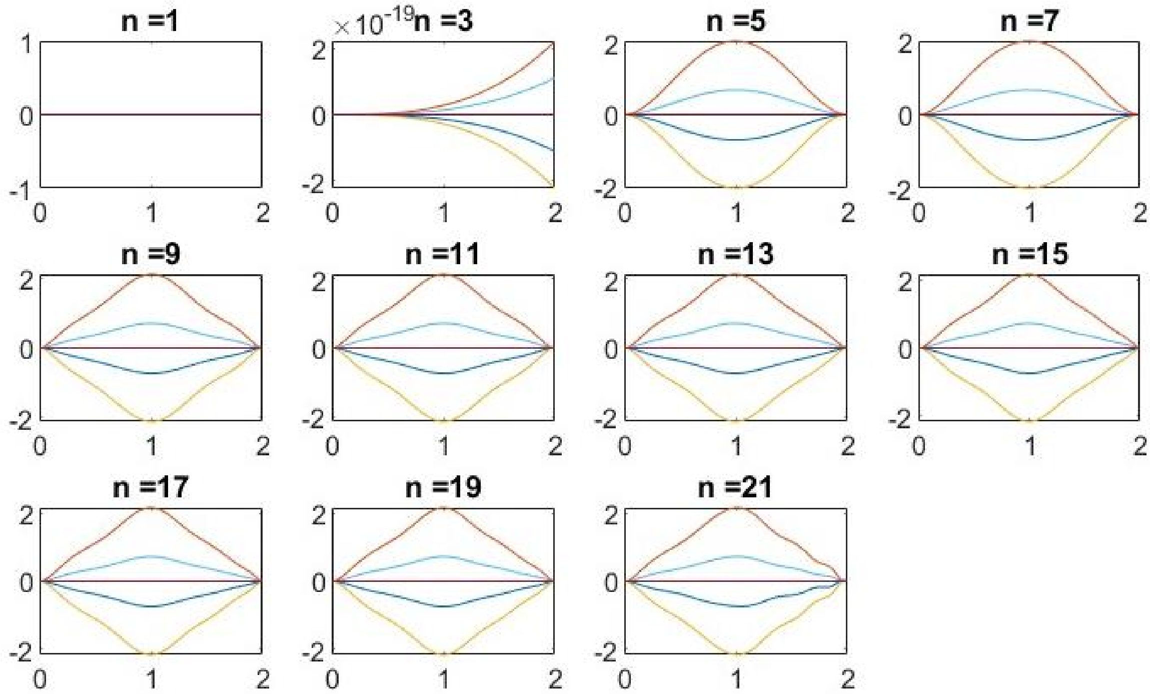

Figure 6 Smoothed angle functions with different degree polynomials (radians vs time (s))

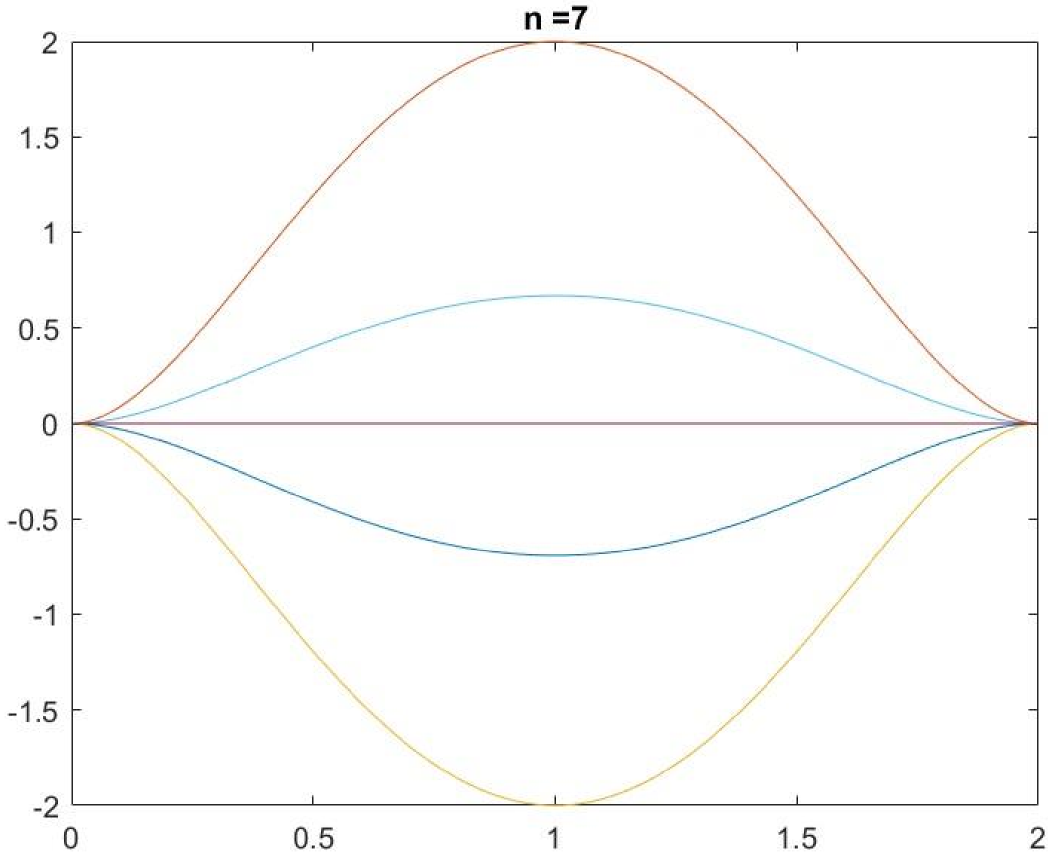

Figure 7 Final smoothed joint angle functions (radians vs time (s))

For this smooth motion, we used simscape to determine the joint torques with and without an exoskeleton spring to determine the effect of the spring as well as determine the optimal stiffness.

Chapter 3: Results

Using the time series produced from the smoothed angle functions resulted in a smooth squatting motion (figure 8). The torque output was plotted (figure 9) which displays a much smoother torque function without the “spikes” that were seen before (figure 5). I computed the baseline energy cost without any springs using these computed torques. I now had a simple actuated model that could serve as the basis for testing assistive device design iterations.

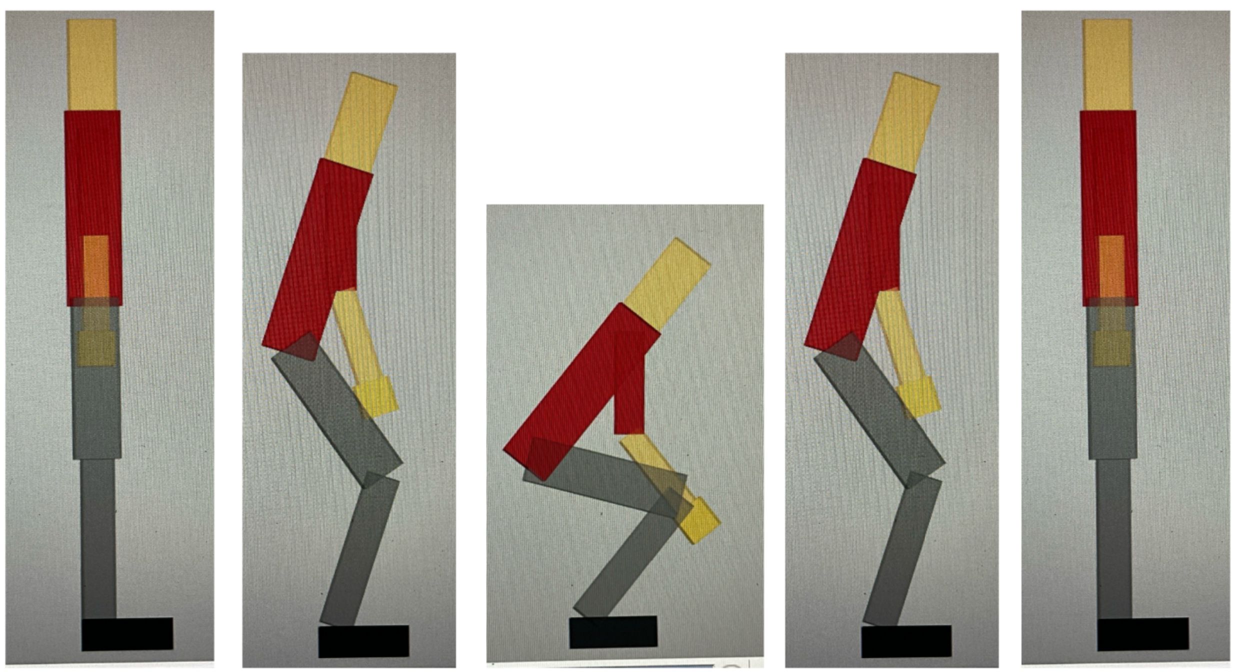

Figure 8 2D Simscape Multibody human model squatting motion

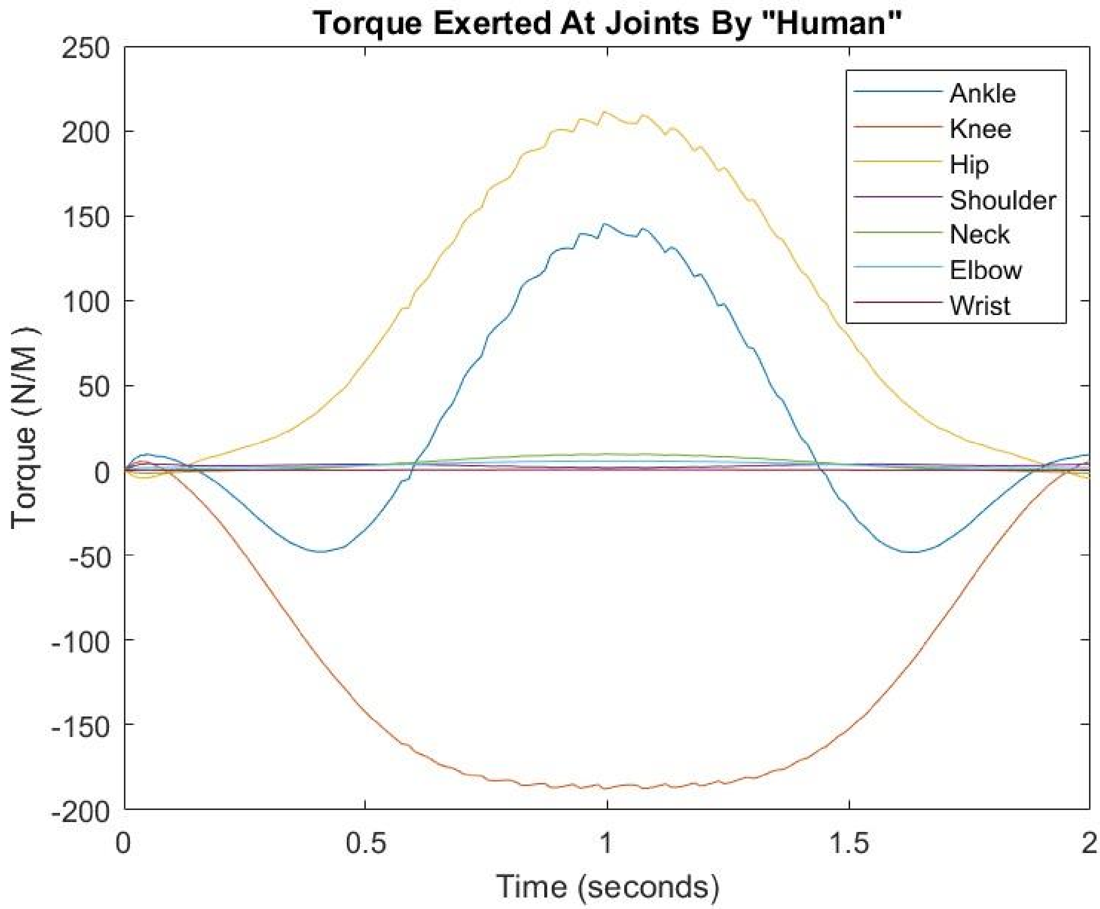

Figure 9 Joint torque after angle smoothing

Adding a spring-like exoskeleton and testing a range of spring stiffnesses. I added a spring force with its end points spanning from the back of the upper leg segment to the back of the lower torso as seen in (figure 10).

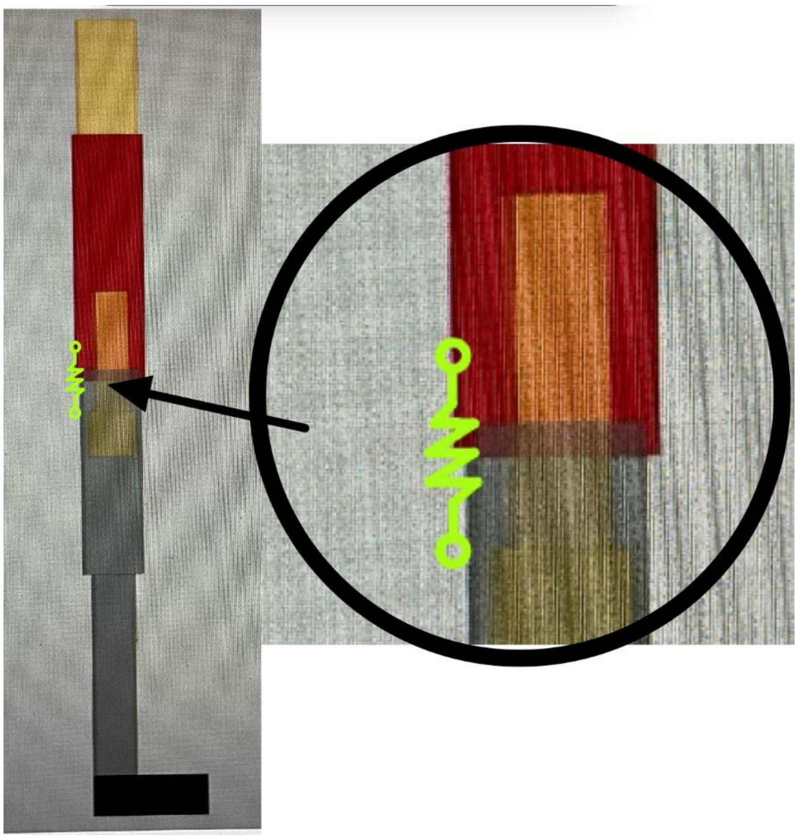

Figure 10 Simscape human model with added spring

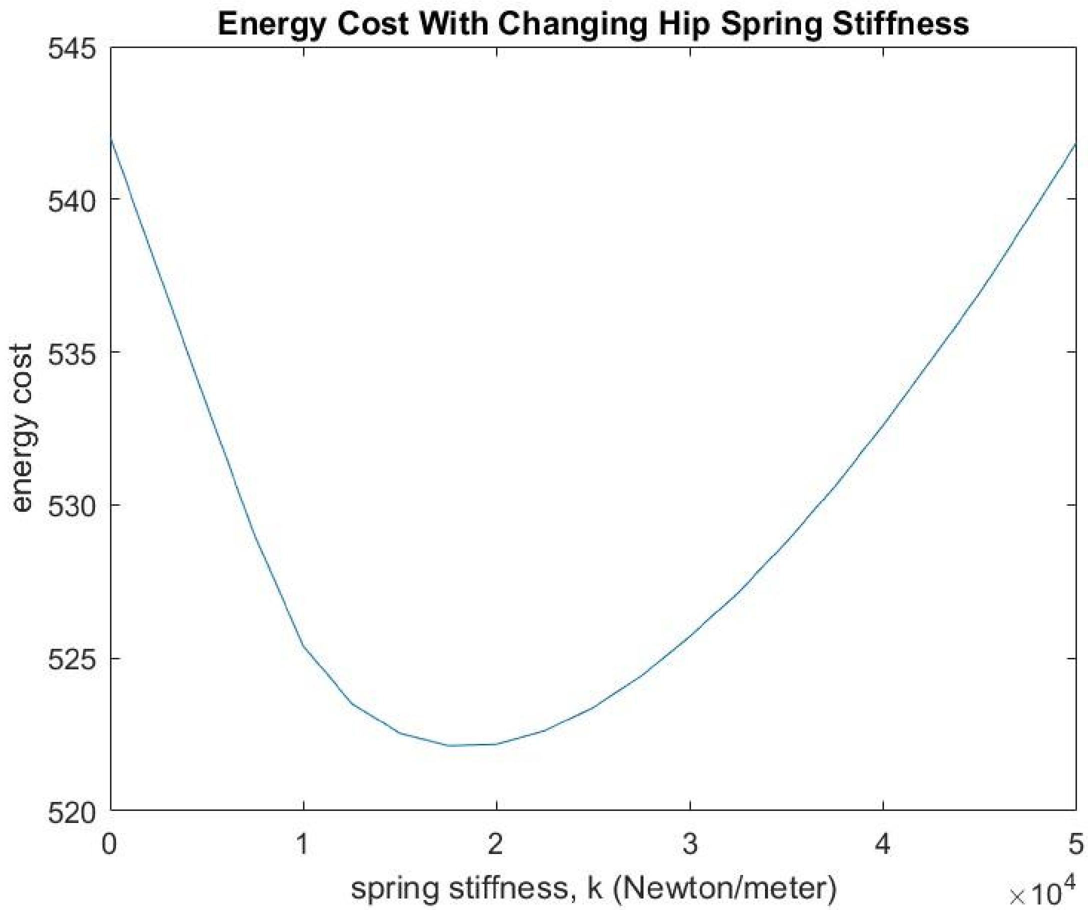

Figure 11 Energy cost vs spring stiffness

We used a MATLAB loop to run the simulation several times while changing the spring stiffness and keeping the natural length constant which was equal to the spring distance while standing, or in other words, there was no pre-load at the initial standing position. As seen in figure 11, which is a plot of the spring stiffness versus the energy cost, there is an optimal spring stiffness that reduces the work required for the squatting motion.

Next, I held the spring stiffness constant (at the optimal stiffness found previously) and made a loop in order to change the springs natural length (the length at which there is zero force) or, in other words I was varying the spring "pre-load" at the standing position. The plot generated, seen in (figure 12), was similar to the one that was made while varying the spring stiffness and shows that there is an optimal natural length for this spring stiffness.

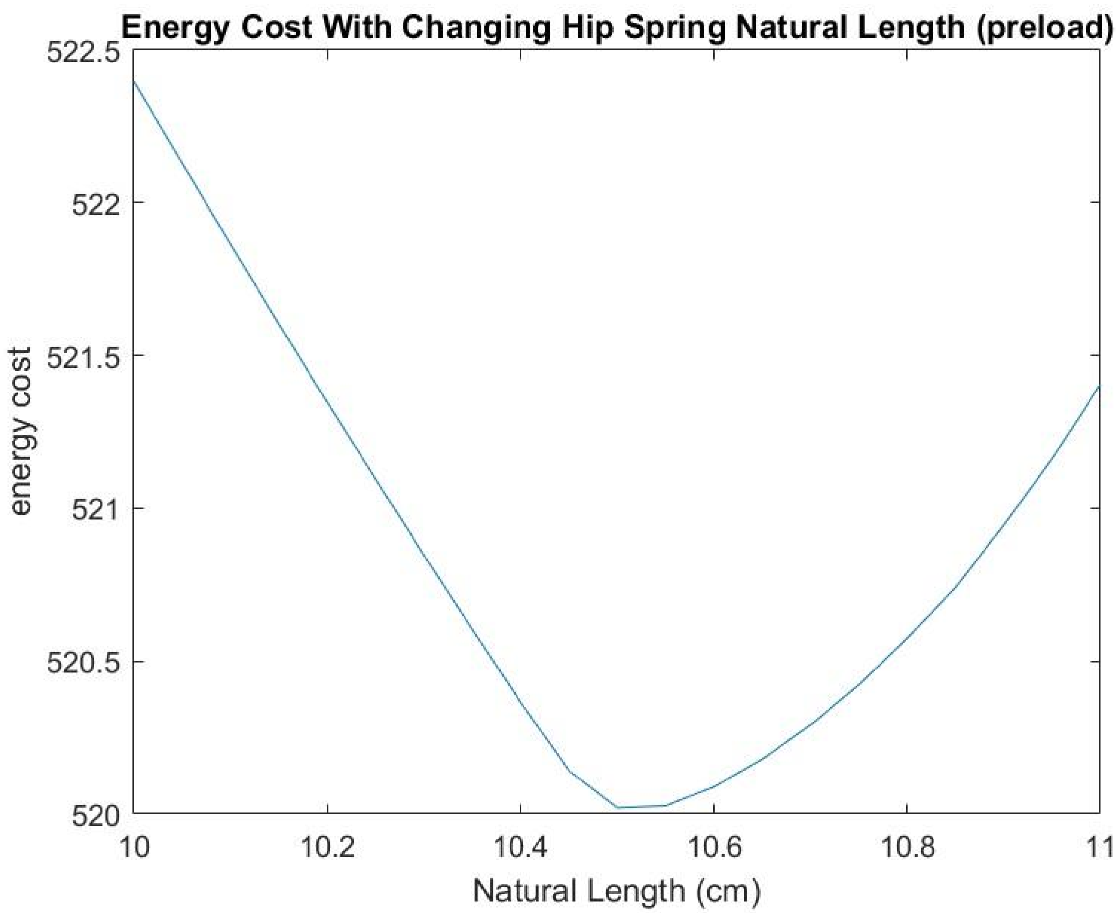

Figure 12 Energy cost vs spring natural length

Chapter 4: Conclusion and Future Work

This work has located a gap in current human centered design methods that would be beneficial if explored, built a foundation for a simple iterative approach to assistive device design and displayed qualitative evidence suggesting this approach could be useful in assistive device design. However, much more work is needed in order to realize a general framework for assistive device generative design.

Future work includes methods for iterating through more design parameters, adding more than one spring, and moving the attachment points of the springs iteratively, adding different types of device elements such as solid linkages, and joints that could potentially create various four-bar type mechanisms, and dampers etc.

With every additional element and parameter added, a simulation must be run in order to test the device configuration. This could conceivably become computationally expensive exponentially fast, so careful thought would likely have to be given to how to reduce this cost. This might be done through a more intelligent design optimization process instead of simply trying all possible combinations of device elements and parameters. This cost could be reduced by making reasonable simplifications/ approximations and assumptions such as reducing the number of actuated joints. There are many optimization algorithms and even several methods of generative design that could be reviewed that could help plan a route forward.

Another future work is detailed model validation. In this study, I did my best to make a model that would be representative of a human with the correct dimensions, mass, and movement, but studies would need to be performed to determine how closely this model resembles the physics of an actual human. Also, it might be useful to determine what aspects of the model that need to more accurately depict a human and which parts could be overlooked in order to simplify calculations and reduce simulation time.

Finally, in order to achieve a true generative design method, I believe it would be necessary to allow for several input parameters that you would pass to the algorithm that it process through and generates many design concepts that fullfill those design requirements. These parameters would include the general task to optimize for that could be used to determine input forces. The design process could also include volume constraints that would be necessary to determine, since there are many limitations as to where you can add device elements such that they wouldn't restrict movement, or add too much weight. Finally, ergonomics and human factors would have to be considered such as comfort and even "form factor" or artistic design, because if you make a device that functions well in addition to visually attractive would make it more likely to be used.

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