The Squat Bot: A Minimally-Invasive, Low-Cost Exoskeleton for Sitting and Standing

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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***Abstract* – Assistive wearable lower limb exoskeleton robots have many areas of application, including increasing mobility and overall health of the elderly. An important aspect of ongoing research in this field is developing such assistive devices and enabling safe human–machine interaction. Presented is a preliminary design and prototype for a device that assists a human user when sitting and standing. Its low cost and minimally-invasive design should allow for everyday use, as opposed to restrictive and cost-prohibitive rehabilitation designs. The structure utilizes an off-the-shelf "invisible chair" as a support for weight and stability. Patients should be able to sit and stand seamlessly with this device, while only contributing ankle mobility and minimal muscle effort.**

I. INTRODUCTION

A. Overview, Motivation, and Background

Over time, the human body inevitably deteriorates and the things we now take for granted become much more strenuous. According to Laporte, Chan, and Sveistrup [1], aging makes sitting and standing more difficult. Elderly people's muscular strength decreases, as does the range of motion in the hips and the knees. With an additional worsening in reaction time, these all combine for a much higher risk of falling. One in four elderly people report falling every year [26]. Without help, elderly people are prone to adopting more sedentary lifestyles, which in turn tends to have detrimental health effects over time [2]. This technology could improve the quality of everyday life for a segment of the population whose rapid growth is highlighted in Fig. 1.

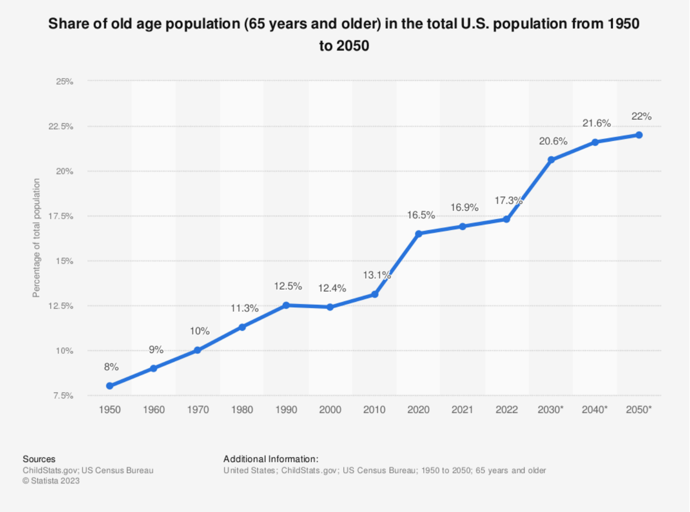


Fig. 1. Increases in the Elderly Population [3]

Exoskeletons are one of the most common assistive technologies that can be found in the rehabilitation field to date. The ideal exoskeleton for an elderly person is wearable and usable throughout the entirety of the day that will not damage their bodies. A minimally invasive, low cost, lightweight exoskeleton would be able to accomplish this. The field of exoskeletons is still in its infancy and there is much more work to be done ahead for both the upper and lower body. Additionally, because this technology is still in the experimental stage, it is also very expensive. In rehabilitation, the current exoskeletons are usually not transportable and the patient must visit a facility for treatment. Meanwhile, the novelty of this project is the portability of this device, and the implementation of existing lightweight technology that allows us to maximize performance while reducing cost and weight.

B. Literature Review

Several robotic exoskeletons have been designed to aid with lower-limb function. An overview of state-of-the art exoskeletons by Alberto et al. [4] provides a useful framework to differentiate the designs, as shown in Fig. 2. Given that our area of interest is exclusively lower-body, exoskeletons first vary in material from soft [5] to rigid [6], as shown in Fig. 3. They vary in actuation from passive [7] to active [6]. Finally, these designs utilize different powered technologies, such as electric motors [7], hydraulics [4], and pneumatic systems [8]. The state-of-the-art lower-limb exoskeleton technologies appear to have exhausted most areas for study in these three categories.

The gap present in this literature however lies in the final two categories: Purpose and Application Area. Our purpose is related to performance, although aligned with everyday assistance. Our application area is civilian, specifically the elderly.

There is not yet a mechanical solution to provide sitting and standing assistance for the elderly through the lens of affordability and the lack of immense weight. From the existing technology, there is not yet a system that is completely portable, non-invasive, and affordable. Many of the experimental designs also involve pneumatics, which are extremely loud [10]. Shipping companies are experimenting with exoskeletons designed for heavy lifting, as shown in Fig. 4, but are incredibly restrictive in terms of mobility [11]-[12]. They enable a user to move large amounts of weight, but are bulky and heavy. Other designs are built for extreme conditions, not for the average person, nonetheless an elderly person. These projects for military applications, such as Harvard's soft exosuits, are expensive and not yet proven effective. They are designed to support greater than 80 pounds of soldiers' equipment, heavier than a person's everyday loads [5], [9].

Other exoskeleton designs for the lower body are centered around walking and gait analysis, like that shown in Fig. 5. In those designs, the subject typically has trouble with the biomechanics around their ankle and foot. This project targets those with weak quadriceps or gluteal muscles. On average, both the bones and muscles start to deteriorate at age 30. By age 60, the rate at which a human loses muscle mass is significantly faster than the rate at which their bone density decreases [14]. This means that many elderly people can still walk, but will experience issues during the motions of sitting down and standing up.

C. Goal for Study

The goal of this study is to investigate potential designs for a low-cost lower-limb exoskeleton that can assist a patient with sitting and standing. In particular, a successful design would be non-invasive and practical for everyday applications.

We have developed a low cost device that will assist a patient with transitioning from a full standing position to an upright sitting position, and vice versa. This device focuses on increasing function of both the knee and hip joints, with the assumption that the patient's ankles function without assistance. Surprisingly, elderly people generally retain their ankle mobility, which enables the creation of solutions limited to the hips and knees [1].

With a fairly light device, the user is able to sit and stand with ease, as the lower limb exoskeleton will guide them through the necessary motions of both sitting and standing.

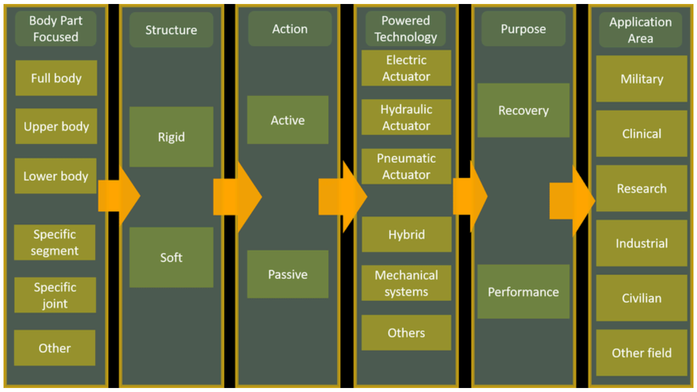
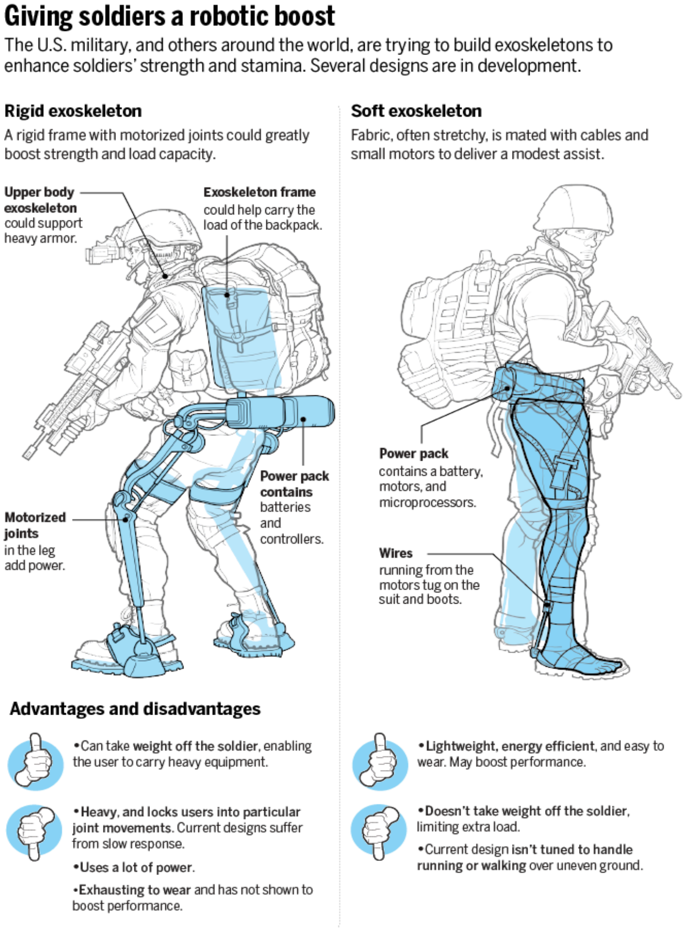


Fig. 2. Categorization Model for Exoskeletons [4].



Giving soldiers a robotic boost

The U.S. military, and others around the world, are trying to build exoskeletons to enhance soldiers' strength and stamina. Several designs are in development.

Rigid exoskeleton

A rigid frame with motorized joints could greatly boost strength and load capacity.

Upper body exoskeleton could support heavy armor.

Exoskeleton frame could help carry the load of the backpack.

Power pack contains batteries and controllers.

Motorized joints in the leg add power.

Soft exoskeleton

Fabric, often stretchy, is mated with cables and small motors to deliver a modest assist.

Power pack contains a battery, motors, and microprocessors.

Wires running from the motors tug on the suit and boots.

Advantages and disadvantages

- Can take **weight off the soldier**, enabling the user to carry heavy equipment.
- **Heavy, and locks users into particular joint movements.** Current designs suffer from slow response.
- **Uses a lot of power.**
- **Exhausting to wear** and has not shown to boost performance.

- **Lightweight, energy efficient**, and easy to wear. May boost performance.
- **Doesn't take weight off the soldier**, limiting extra load.
- Current design **isn't tuned to handle running or walking** over uneven ground.

Fig. 3. Rigid vs. Soft Exoskeletons for Military Applications [9].

Fig. 4. Industrial Exoskeleton [13]

Fig. 5. Rehabilitation Exoskeleton [15]

We have successfully designed a rigid exoskeleton. Unlike other rigid exoskeletons, however, the design incorporates existing lightweight technology that is able to regulate and hold the weight of the user in the exoskeleton. Specifically, the usage of an invisible chair (Fig. 6) minimizes the amount of material needed to control the weight of the user. We attached our mechanical device to the outer portions of the lower limbs and attached them to the user's body at the hip, with a lifting belt, and to the thighs, with straps that hold the invisible chair and frame of our device together (Fig. 7). Aside from the weight bearing structure, the frame of the structure that is attached to the motors on the joints, which is the only metal material in our design aside from bearings, making our design very different from previous designs. The Squat Bot is less than 50 kg and produces noise less than 40 Db, which is unique in comparison to rehabilitative designs on the market—it is specifically designed for at-home, everyday use.

Fig. 6. Invisible Chair [16]

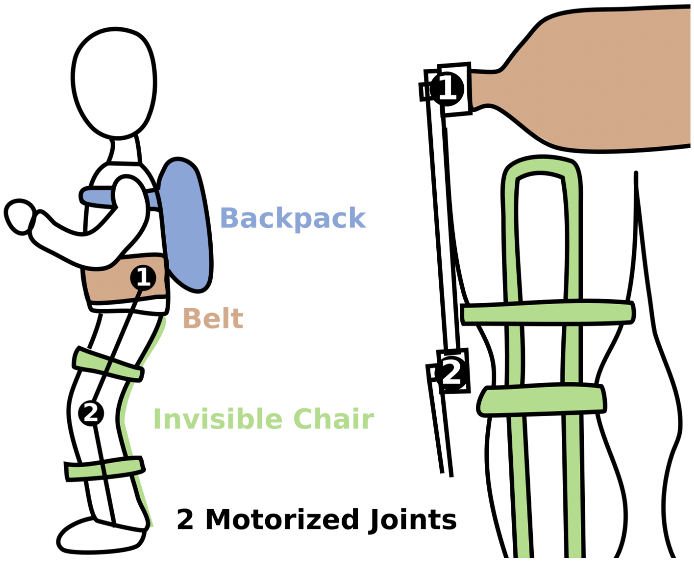


Fig. 7. Initial Design

II. METHODS AND MATERIALS

A. Actuator Selection

Three possible mediums of powered actuation technologies are used in common exoskeletons: hydraulics, pneumatics, and electronics. Pneumatic actuation requires invasive placement and a loud pump. Hydraulics also requires a pump and a storage system for the fluid. The storage system could be attached to the body, but the dense nature of hydraulic fluid would make it difficult to store. For our purposes, the best option was to utilize electronics. This requires a powerful power source, which was obtained at a low cost and moderate weight and stored in the backpack from a portable battery bank.

Additionally, linear actuators and electric motors are much stronger than they used to be. An example can be found in the sudden rise of electric scooters and skateboards. Previously, it had been too difficult to create and consistently power a small motor that could deliver high torque. Ultimately, motors were chosen over linear actuators because they are much more compact, which aligns with our specifications. Therefore, we opted to place one motor on each knee and one on each hip, so in total we utilized 4 motors in our design.

While DC motors are cheap, stepper motors are the better choice because of the high holding torque. The heavy weight of a person and the slow nature of the desired movement make it necessary for the motors to withstand slow or even stopped movement. If at any point in the movement the system stalls, it is likely that a DC motor will burn out. The stepper motor could still potentially burn out in a worst case scenario, but the documentation provided by manufacturers gives detailed information about just how much torque and current the motors can take before they fail. This information is necessary to understand and prevent failure by mechanical load, which is what helped guide us in motor selection.

Deciding the necessary stepper motor model was dependent upon torque calculations for both the hip and knee joints on the specific dimensions of our test subject. Eguchi [7] provides a useful model with a subject similar in dimension to our own subject. Shown in Table I are the dimensions taken from our subject used in the torque calculations, and Fig. 8 provides a diagram of the motions modeled.

The following calculations were made to predict the maximum torque experienced at each joint in the system. Equations (1) and (2) model the human body as a four-part linkage (trunk, thigh, shin, and immovable foot), and the scenario in Fig. 9 where linkages are in the position of maximum torque. This was presumed in accordance with the approaches detailed in the Eguchi [7] paper, including a 20 degree angle between the thigh and horizontal plane, and 45 degree angle between trunk and horizontal plane. The masses values, m, are approximated as percentages of total body weight according to data collected in Plagenhoef [25]. The total weight of the subject, W, was measured as roughly 70 kg. The symbol g is used to represent the acceleration of gravity, 9.81 m/s^2. The length values, L, each represents the real measurements of the subject we designed the device for. L_{knee}, not shown labeled in the diagram, is a measurement of the knee joint itself. These values calculated using these equations calculate the total torque for both motors.

$$T_{knee} = (L_{thigh,ref} \cdot m_{thigh} \cdot W \cdot g) + (L_{knee} \cdot m_{trunk} \cdot W \cdot g) \tag{1}$$

$$T_{knee} = 0.483(0.1)(70)(9.81) + 0.088(0.3295)(70)(9.81) = 53.08\, N \cdot m$$

$$T_{hip} = L_{trunk,ref} \cdot m_{trunk} \cdot W \cdot g \tag{2}$$

$$T_{hip} = 0.549(0.3295)(70)(9.81) = 124.22\, N \cdot m$$

*The torque requirements above are not for each individual motor, rather the sum of the torque required at the joint for both legs.

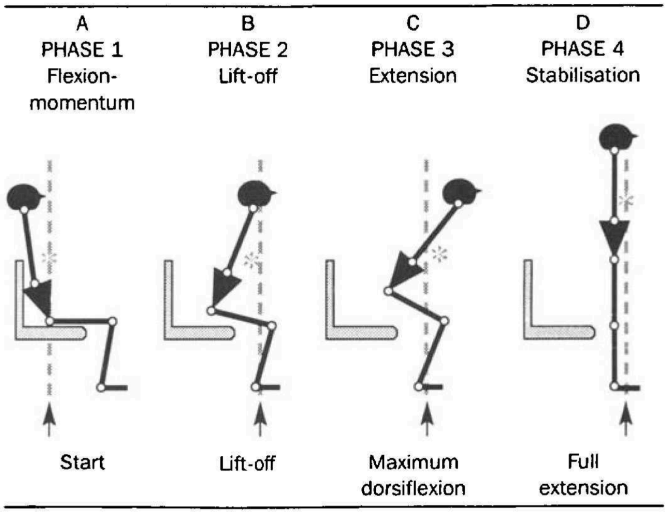


Fig. 8. Motion Diagram of Standing Biomechanics [1]

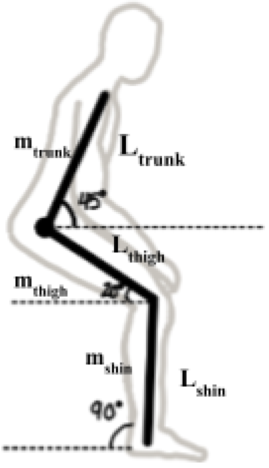


Fig. 9. Labeled torque calculation diagram

TABLE I. TEST SUBJECT DIMENSIONS

Link	Length (m)
Full Height (Standing)	1.829
Trunk (Hip to Neck)	0.549
Thigh (Hip to Knee)	0.483
Knee (Joint)	0.088

However, other mathematical models of human sitting and standing differ on the maximum values of the torques. Bartenbach, Gort, and Riener determined that the hip torque would actually be less than the torque on the knee, with remarkably close but opposite values to our calculations [17] for the two joints. However, since both of our maximums are within the same range and the same motors will be used on all joints, prototyping and testing continued simultaneously with further confirmation of these calculations.

These torque values confirm that the purpose of the machine must be assistive rather than independently functioning. Within our specifications for budget and weight, it was simplest to begin with regular-performance NEMA 23 stepper motors [18] driven by standard NEMA 23 motor drivers [19] with a gear box. The motors were selected to provide a maximum torque rating of 70 N*m, which is more than the amount of torque needed to raise the user in either joint (assuming there is no input from the user's muscles). Since the system is only designed to assist, rather than replace the movement, this should be more than enough torque. Additionally, this means that the motor will not be running at full power throughout the movement.

B. *Manufacturing and Material Selection*

The structural prototype components were designed in Solidworks and 3D printed in ABS plastic, as shown in Fig. 10. Although PLA is stiffer, a PLA part is likely to crack under the applied stress. The parts were printed thick enough with high infill to resist any compressive forces; ABS plastic is tougher, making it able to withstand the necessary higher tensile stresses.

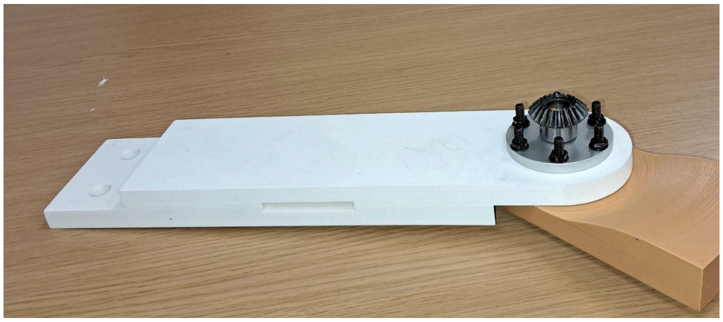


Fig. 10. The High Infill Plastic Frame Piece (White)

The shafts perpendicular to the motors, responsible for transferring motion from the motor to the full frame, were originally designed in aluminum. This part is one of the most crucial in the design and is responsible for withstanding some of the greatest stresses. Unfortunately, these parts were improperly manufactured and not ready for use in the final prototype. For this reason, ABS plastic shafts were used in replacement in the final design. However, the shafts would be stronger and reduce backlash in the gears if made out of aluminum or steel as originally intended and designed.

C. *Full Design*

The design is a stable device that assists in standing and sitting. It utilizes an already developed mechanical system—an invisible chair, as shown in Fig. 6—that provides support in the legs to take pressure off of the lower limbs. It is attached to a workout belt around the hips that not only holds the leg supports in place, but provides back support for the user. Additionally, a small backpack contains the power source and control electronics. Our design, as shown in Fig. 7, uses four motors, two on each leg, with one on the outside of the knee and one on the outside of the hip. All of this is attached to the user's legs with 3D-printed frames.

The exoskeleton assembly is shown in Fig. 11. The blue elliptical shape represents the belt that holds the user's core in place, and the gray linkages connect the hip to the belt. The green and orange parts make up the thigh linkage, which was split in two to fit in the 3D printer. The cyan linkage connects the knee joint to the rest of the leg. The pink blocks represent the NEMA 23 motors with integrated gearboxes. Each motor drives a perpendicular shaft attached to the frame via 1:1 bevel gears (Fig. 12).

The invisible chair incorporates velcro straps that are designed to go through the slots on the linkages, holding the frame in place as these straps are strong enough to support the movement of both the invisible chair and the exoskeleton. When taut, there is no wiggle room for the exoskeleton to slide and slip from its desired position on the user's body. The velcro straps are extra wide with plenty of surface area to make sure it does not come undone. While the velcro is not shown in Fig. 11, the invisible chair is modeled in gray.

We expect the knee and hip joints to be the most likely points of failure, as the shaft connected through the bearing is subjected to high torque from the motor. This leads to a high amount of shear stress near the base of the shaft. In our final prototype, however, the plastic shafts did not shear. When manufactured correctly, the metal shafts will be an even better implementation into the system. Fig. 13 shows the plastic shaft that was 3D printed with the aluminum shaft next to it. For cost reasons and efficient material usage, the aluminum shaft was made out of two pieces of stock.

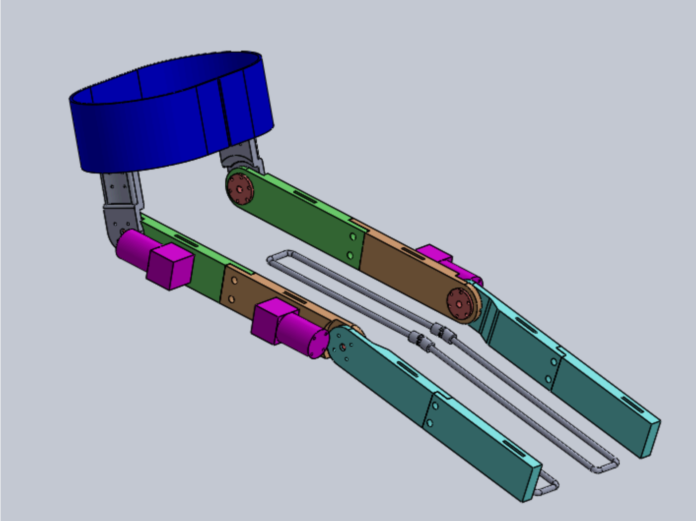


Fig. 11. CAD Model

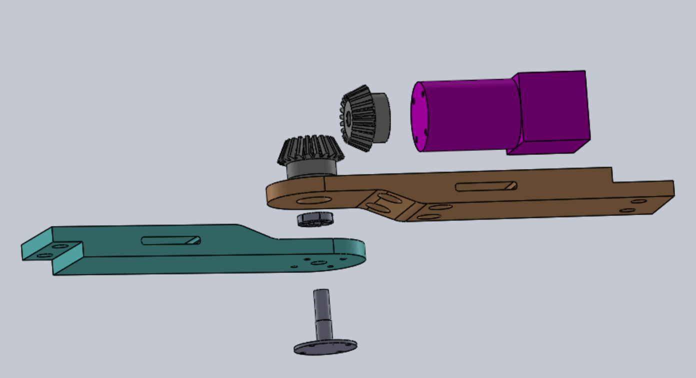


Fig 12. Exploded CAD Joint Model

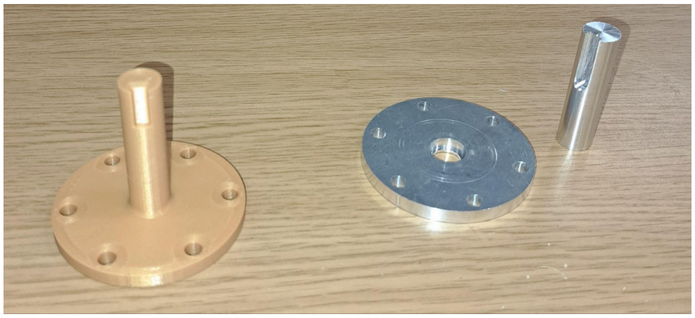


Fig. 13. Plastic Custom Shaft (Left) and Aluminum Shaft (Right)

As seen in Fig. 12, the motor's power is directed 90 degrees using 1:1 bevel gears as the motor would have been too heavy to mount directly into the joints. The gears were sourced from Amazon and work very well during continuous operation. However, there are not many teeth so the resolution is low, sometimes inducing a substantial amount of backlash to the system.

Fig. 14. Steel 90 Degree Mounting Brackets [23]

Steel mounting brackets, as shown in Fig. 14, were used to position the motors parallel to the frame. These mounting brackets were made to fit the face of the motor in between the motor and gearbox. The other flange contains slots for adjustable mounting onto the frame. The frame pieces were designed for compatibility with these brackets.

The last component within the joint is the ball bearing. The outer edge of the ball bearing is press fit into the plastic frame, and the shaft shown in Fig. 13 is press fit into the inside of the bearing. The ball bearing serves two purposes compared to previous design iterations with simple hub bushings. One benefit is reduced friction from distributing the load over the balls' much smaller surface area. The second benefit is strengthening the alignment of the shafts. The bearing helps connect the frame and shaft while providing support against shaft misalignment during the system's operation.

D. *Control Development*

The following stages compose the ideal control system development:

1) Create a motorized lower-limb exoskeleton prototype that successfully supports a person's weight and movement when sitting and standing. Control (start/stop) will be via computer attachment.
2) Make the system portable and operable via a button press.
3) Incorporate a closed-loop control system (PID) to adjust for variability in movement.
4) Use electromyography (EMG) sensors to automatically detect sitting and standing, making the device usage seamless in everyday life.

Initial control was via direct computer connection to the Arduino Nano. After testing, we incorporated a physical switch to start and stop the movements of our exoskeletal device, which is the current state of the design. In the future, a closed-loop control system allows for real-time adjustment of the motor outputs in order to account for the user's organic movement, with the aid of stepper motor encoder readouts [20]. Finally, in a fully-developed control system, EMG sensors will be integrated to replace the physical switch and allow the system to run more seamlessly.

To begin control development with practical motion, four of the chosen stepper motors were set up according to Fig. 15. The setup was successfully tested with code to run all four motors simultaneously at a constant velocity. The new system runs using the AccelStepper Arduino library in order to smoothly accelerate and decelerate multiple motors between stages of motion. The toggle switch tells the system to sit or stand, and the emergency stop button pauses the motion. All four motors are powered by a portable power bank, rather than an outlet power supply. While we have not tested the full battery life of the power bank, we have conveniently located the battery in an exterior pocket. This allows for a modular battery system if the performance is shorter than expected.

In order to understand the best range of motion for motor operation, we conducted video analysis of our test subject sitting and standing. The setup and motion tracking view is shown in Fig. 16, and some graphical results are shown in Fig. 17. Five trials were taken for more accurate calculations and more confidence in our angular values. Table III illustrates the averaged quantitative results of these five trials. Notable takeaways from this summary and from Fig. 17. include the two phases of hip motion, with one phase being relatively linear and the other parabolic. When conducting the action of sitting or standing, the hip begins to move before the knee. The resulting plots of angular position, velocity, and acceleration reveal trajectories that can be roughly approximated by the smooth acceleration and deceleration from the AccelStepper.

A principal challenge for control development was the lack of parallel processing capabilities on the Arduino Nano. If controlling stepper motors from "scratch" on an Arduino, the sequential command format necessitates simulated "simultaneous" motor operation by stepping each motor one at a time, but with mere milliseconds between each pulse. This problem is solved in part by the use of AccelStepper functions, which move multiple motors at once with preset acceleration and maximum speed values. The motors are each given target positions and told to begin motion at the same time. Additionally, this dilemma is also addressed with the use of Arduino interrupt functions, which dedicate separate processing power to check for state changes on specific pins. The Nano's two interrupt pins were used for the sit/stand toggle switch and the emergency stop button.

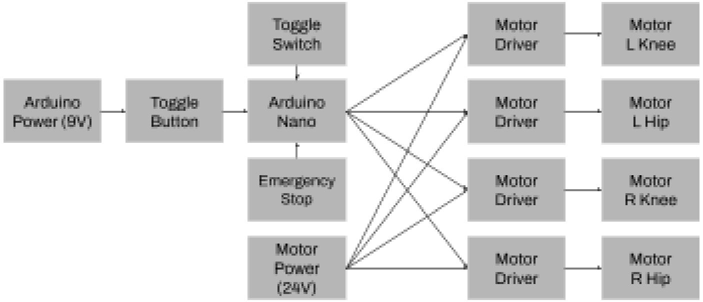


Fig. 15. Control and Electronics Overview

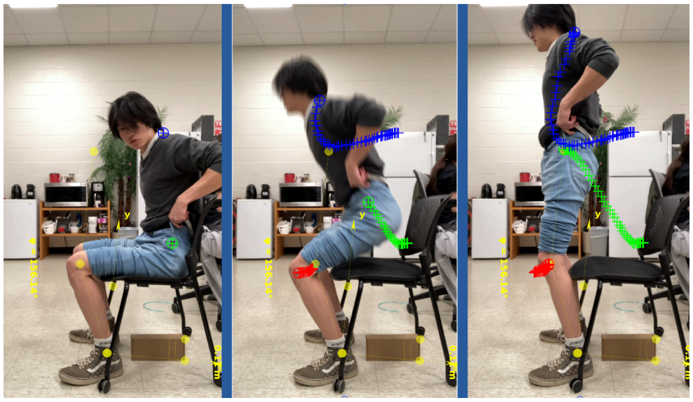


Fig. 16. Video Analysis in Progress

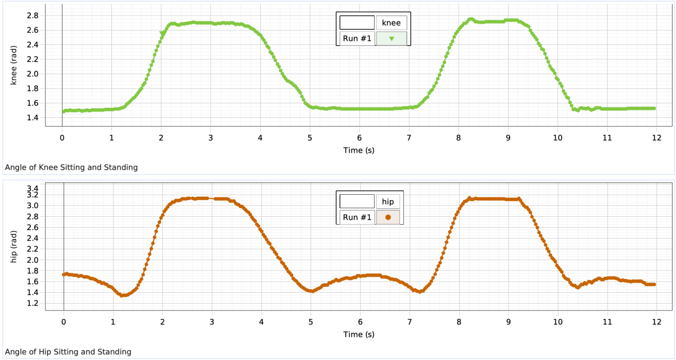


Fig. 17. Knee and Hip Angles While Sitting and Standing

With the more accurate benchmarks from the video analysis (as compared to Table II), each motor was assigned a target position (these positions are shown in Table IV). The code runs the motors simultaneously through three phases for both sitting and standing. However, the backlash in the system has affected the prototype's ability to meet these desired benchmarks. In order to account for the backlash, we have added a small constant to the target positions to dictate them to move more than previously calculated.

TABLE II. DEGREES OF FREEDOM

Joint	Sitting angle	Standing angle
Knee	60°	120°
Hip	50°	100°

TABLE III. SITTING AND STANDING JOINT MOTION

	Knee	Hip
Sitting	-1.2 rad	-1.68 rad
		0.24 rad
Standing	1.2 rad	-0.35 rad
		1.765 rad

TABLE IV. TARGET POSITIONS FOR MOTORS

	Phase 1	Phase 2	Phase 3
Hip Stand	3015	3765	0
Knee Stand	3080	3080	0
Hip Sit	0	3542	3015
Knee Sit	0	3080	3080

E. Evaluation

The final design, as shown in Figures 18, was evaluated according to a preset list of specifications. The most important specifications for this final product were that it be minimally-invasive, low-cost, and will not weigh more than 50 kg. The forces that need to be resisted depend on the subject's physical parameters. In order to be fully seated, we used the known sitting and standing angles to determine the degree of bending necessary at the knees and the hips. For the knee, the seated angle is 60° and the standing angle is 120°. For the hip, the seating angle is 50°, and the standing angle is 100° [21]. These are summarized in Table II. A successful device will achieve this range of motion for the patient.

To test the usability and accuracy of our device, we conducted several continuous trials sitting and standing with our test subject. When doing so, we found that the user could move when meant to be stationary, indicating slop in the system. Despite this backlash, our overall desired motion was met fairly quickly, quietly, and safely. A visual breakdown of our specifications is provided in Table V that addresses our goals and outcomes for our final prototype.

TABLE V. SPECIFICATIONS

Criterion	Benchmark	Achieved
Weight	50kg/110 lb	Achieved 37kg/82lb
Range of Motion	Knee 60° - 120° Hip 50° - 100°	Achieved for Knee Hip is missing 11°
Operating Time	5 - 10s	Achieved Sit/Stand in 5s
Cost	\$4000 - \$10000	Achieved Under \$2000
Reliability	Does not malfunction; always moves in the correct direction	Achieved with laptop, needs more testing for buttons
Minimally Invasive	Does not impede day-to-day function	Needs gear release mechanism for walking

Fig. 18. Final Prototype in Action (Standing)

III. DISCUSSION AND CONCLUSION

The current design assumes that the user will provide enough power on their own to keep from overloading the motors, hence why this is considered to be an assistive exoskeleton technology. However, this may prove to be incorrect in the event of a user falling or moving irregularly. In that case, it would be wise to incorporate a ratchet-style system that enables the chair to progressively lock in place, supporting any extra weight throughout the movement. If changing mechanical elements of the design, or increasing its scope to full action rather than assistance, it is necessary to confirm the torque calculations with additional sitting and standing models. This is required to understand the true maximum torque that could be exerted on the actuators through the system's operation.

The highest-priority future work on the mechanical design is to develop a mechanism for disengaging the bevel gears. The current prototype does not allow the user to freely move with the motors turned off. In order to be seamless and useable every day, it must be worn at all times, with little obstruction to other motion.

The next most important work will reduce backlash in the system. An ideal final prototype would have incorporated aluminum or steel shafts that are much more resistant than plastic to reduce slop and deformation. Solutions for the bevel gears include switching to spiral gears or increasing the number of teeth. Spiral gears would greatly reduce backlash but are much less tolerant to misalignment. In comparison, spur gears can shift around from irregular human movement while still mating and transmitting torque. When testing, they were observed to fall back into place after brief misalignment. Gears with more teeth will have smaller gaps between them and therefore less slop.

Future research is needed to improve the design's control systems. A major challenge in exoskeleton control is determining the subject's intentions when moving to provide the necessary cooperative assistance and minimizing interference of this desired motion. The design can be modified to incorporate electromyography (EMG) without significant rework. Currently, the exoskeleton's motorized hip and knee joints are controlled via a button or computer connection until these EMG sensors are incorporated into the system. Besides this, PID control and non-constant speeds may better approximate the joint motion observed. This is especially relevant for the parabolic motion in Phase I of the hip joint when standing (and in Phase II when sitting). PID will require the setup of encoders on each motor, which have already been purchased but must be wired in and accounted for in the code.

The proposed design is a valuable tool for the healthcare industry and for elderly consumers. Considering the relatively low amount of information relating to lower limb exoskeletons, the research area is novel and useful. New high-torque motors and CNC manufacturing will allow for an even more compact, low cost design; a few years ago, motors of the required power-to-weight ratio did not even exist. Moreover, the parts are simple enough to be manufactured and altered by university students. This implies that a commercial manufacturer could feasibly mass produce the design at a low cost and make this application accessible to a wide variety of individuals. The Squat Bot is a relatively inexpensive device with the ability to enhance the quality of life and make daily tasks easier for a significant segment of the population. We hope that future students will build on our progress and continue to make the device a reality.

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