Design of a Robotic Rollator for Sit-To-Stand and Walking Assistance of Older Individuals with Mobility Disorders

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Many elderly people suffer from a loss of mobility due to musculoskeletal disorders, neurological conditions, diabetes, frailty, or other impairments, and thus require assistance during walking and Sit-to-Stand (STS) transfers. Majority of commercially available mobility assistance devices are passive walkers, rollators, and canes which provide limited walking support and minimum support while standing up. Persons needing STS assistance typically rely on external forces applied by a person or a device to help them stand up.

In this thesis, we will present the design and functionalities of SkyWalker, a novel lightweight robotic rollator with active STS assistance. It is made for providing powered walking support on different terrains. STS support relies on a bilevel handle design and consists of active vertical lift and forward translation support during STS, then a handle change by the user to fixed handles once standing. Stand-to-Sit transfer follows the reverse order. To evaluate the SkyWalker design and control and identify areas of improvement, we conducted experiments with healthy young adult subjects. A biomechanical study on STS motions compared 6 different STS trajectories for which the kinematic, kinetic, and user feedback were collected. Additionally, we tested SkyWalker's ability to support walking on different surfaces, on uneven terrain, and around obstacles. Finally, we conducted an interaction study to test voice control as a potential interface to allow the user to control the direction and movement of SkyWalker independently.

The experiments showcased the walker as a potential assistive device and identified limitations to be addressed prior to experiments with frail subjects. The data collected and the feedback from the subjects show great potential for the robot to be used as an assistive device in an indoor and outdoor environment.

Acknowledgements

I would like to thank professor Katja Mombaur for her unlimited and timely support throughout the project. Her vast knowledge in the field elevated this project to it's true potential.

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Finally, I would like to thank my family for their support throughout the project. This thesis would not be possible without them.

Dedication

This is dedicated to my parents and brothers.

Table of Contents

List of Figures

42figure.caption.41

List of Tables

Chapter 1

Introduction

Quality of life is improving worldwide, resulting in an increase in the population's life expectancy. Generally, people face many challenges as they grow older, such as, muscle weakness or other related disorders, stroke, and other neurological diseases [13] [14]. As a result, elderly people depend on others to help them perform everyday activities, which could lead to a negative affect on their mental health. According to Statistics Canada, mobility disabilities is the most common disability type, affecting 1 in 10 Canadian adults. The highest proportion of mobility disability across different age groups is elderly people aged 65 and older which covers 24.1% of total mobility disabilities in the population [1]. 9.3 % reported using multiple mobility devices [15]. More than 18 million people have limited mobility in US and Canada [2]. Similar results can be seen in other developed countries. Using different type of devices may be related to the number of factors such as environmental differences (indoor vs outdoor), health of the user with symptom variability.

Mobility issues are reflected psychologically and have an effect on older populations; people aged 55 with mobility disability start to feel limited in their daily activities [3] . There are ways to improve the ability to do daily activities independently: research shows that there is a correlation between physical activity and mortality; by maintaining and monitoring the total physical activity, the life span of a person can be increased [16]. Also, physical activity can alleviate symptoms of anxiety, stress, and depressions [17]. In order to be able to do physical and daily activities with independence, persons with disability need to be able perform the sit-to-stand (STS) transfer, which are one of the

[1] www150.statcan.gc.ca/n1/daily-quotidien/201203/dq201203a-eng.htm
[2] www.themobilityresource.com/about-us/media-room/mobility-statistics/
[3] www150.statcan.gc.ca/n1/daily-quotidien/201203/dq201203a-eng.htm

most performed activity throughout the day [18], and require adequate muscle strength to shift the body's center of mass upward over the base of support during the movement. It starts with adequate forward trunk lean, followed by precise extension in the hip, ankle and knee joints [2]. Unfortunately, the most common cause of falls in nursing homes is due to an inability to perform the STS [19]. Thus, act of performing STS and walking are very important to perform essential activities and exercise to maintain health body and mind. However, current mobility devices could have a risk on the users' physical health and do not provide STS support. In 2012, Statistics Canada reported that more people are using wheeled mobility and powered devices because they gave users more support than canes, crutches and walkers [4].

1.1 Motivation

There are multiple types of assistive devices, active and passive, which can help persons with disabilities stand up or walk. The assistive devices include wheelchairs, exoskeletons, rollators and lifting devices. Traditional rollators and walkers help individuals with limited mobility or Chronic fatigue syndrome with everyday activities[1]. They are relatively inexpensive, easy to use and obtain. Mahoney et al. show that rollators support the body and improve the walking distance and velocity [20]. However, they have disadvantages that can risk their long-term physical health, including poor posture, which causes shoulder, neck and lower back pain by not distributing the body weight proportionally. They also cause excess pressure on body joints since users have to roll shoulders forward when operating traditional walkers and rollators shown in figure 1.1. Alkjær et al. showed that rollators did not result in an overall less pressure on muscles and joints of the lower extremities [21]. The most commonly used mobility device is cane with 16.4 % of the total population, followed by walkers. However, fear of falling was 30 % higher in cane-only users compared to users of other assistive devices [15], which limited their activity.

For active rollator devices, a common characteristic is using actuators to perform STS and walking. They provide greater mobility and assistance for individuals with musculoskeletal disorders or other impairments while keeping safe body posture. However, most of the devices can be only used in the clinical setting and cannot be used in different environments, and they are complex,heavy, costly to make and maintain. While passive rollators have a less complex system and are lighter in weight generally, they do not generate different STS paths to accommodate different users, and the speed of STS action and walking cannot be controlled based on their needs and preference.

[4]www150.statcan.gc.ca/n1/daily-quotidien/201203/dq201203a-eng.htm

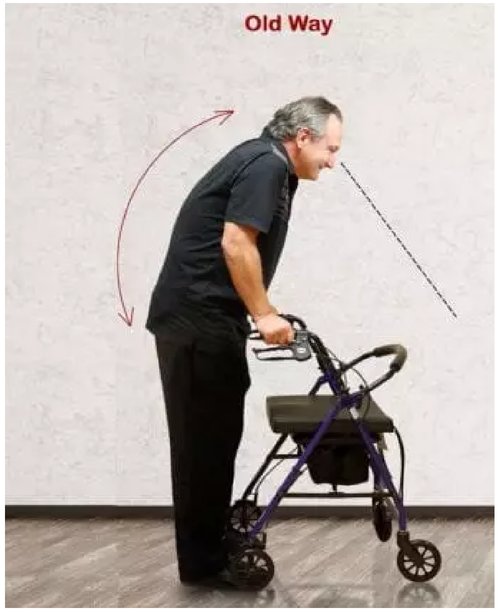


Figure 1.1: Traditional rollator [1]

1.2 Proposed Contribution

This thesis will present the design process and testing of a novel lightweight active assistive walker with STS and walking aid capability SkyWalker, which can easily be maneuvered in indoor and outdoor environments. The goal of the device is to provide an external force to allow users to stand up from a sitting position and to help users walk with ease for longer distances. The device has the ability to be adjusted to accommodate different body sizes for the device to be used effectively. The device is designed to assist 25 % to 30 % of the average body weight of an older adult, as the goal is to give the user the necessary force to perform STS. It is not recommended to support a higher body weight ratio while standing up since an older adult who needs assistance equivalent to more than 30 % of their body weight.

The thesis will show the design development, including prototypes, requirements and constraints that are followed, mechanical testing and biomechanical evaluation of the SkyWalker. Multiple experiments for STS action were performed to test different trajectories. Also, an experiment was conducted to test SkyWalker maneuverability between and over obstacles and in small environments like elevators. Moreover, walking on different types of sidewalks has been performed.

It is important to note that SkyWalker has not yet been tested with older adults with limited mobility. The device's safety and effectiveness need to be tested before testing with the target group. Experiments have been conducted on healthy young adult subjects. The work presented in this thesis needs to be validated with the target user group to define the device's limits and improve on them.

1.3 Thesis outline

Chapter 2 looks into the state of the art of robotic devices with walking and STS abilities relevant to designing SkyWalker.

Chapter 3 discusses the design considerations that have been taken into account. The chapter looks into the importance of determinants of Sit-to-Stand Movement, biomechanics of Sit-To-Stand and how literature describes STS phases. Also looked into the biomechanics of walking, and finally, the chapter will go over the design solution overview.

Chapter 4 discusses the development process of SkyWalker and highlights the design features of the robot.

Chapter 5 will go over the software of the system.

Chapter 6 will discuss the experiments that have been conducted to test SkyWalker functionalities in STS action and walking. Procedures, results and discussions of the biomechanical trails as well as lessons learned from the experiments, are presented. Interaction studies for walking and robots will be presented as well.

Finally, chapter 7 will discuss the limitation of the robot and future work.

Chapter 2

State of the art of assistive devices

Much work has been done on assistive mobility devices, which classified according to their functionalities and control. Traditional walking aids such as crutches, canes or rollators are commonly prescribed by clinicians. Researchers are working on developing different assistive mobility devices, including wheelchairs, exoskeletons, rollators, and lifting devices. However, these devices present limitations because they do not cover many necessities for the user, from STS assistance to walking in different environments like a hospital, nursing home, individual home, and outside space. Moreover, using some assistive devices can be inconvenient, particularly in Exoskeletons and other devices where the user has to wear a harness around their body. The weight of the device is also problematic since it might result in difficulties in controlling said device and introduces difficulties in transporting it to the desired destination. Many assistive walkers can not function in both indoor and outdoor environments, or small areas because of their size, weight or complexity which doesn't give the user the mobility they require for performing their basic tasks/needs independently.

In this chapter, we will review assistive mobility walkers; passive and active walkers. The review will cover different features and levels of assistance each device provides and limitations of using such a device. This chapter also covers the multiple types of assistive devices, active and passive, which can help persons with disabilities stand up and/or walk.

2.1 Active devices

Standing up from a sitting position is a crucial issue that needs to be considered when designing a robotic walker. When studying STS motion in the sagittal plane with symmetry, using a device that can assist in two directions independently (x forward direction and z in the vertical direction), and if users are connected (holding on) to the assistive device , an infinite number of trajectories can be achieved [6] [22] [23]. Some designs provide forward motion as assistance, however by only pulling the users horizontally forward. Those devices might harm the users and will not achieve a healthy STS [24] [25] [26]. Some other devices that also use a single Degree of Freedom (DoF) pull the user vertically instead of horizontally. They can be used if the orientation of the arms of a user is fixed during STS motion, but users' comfort will decrease [27] [28].

More complex systems have been designed with 3 DoF (or more) to provide more help to the users [29] [30] [31]. It is shown that with more DoF, more possible trajectories can be achieved compared to only two (from a sagittal plane), leading to better user satisfaction. However, with high DoF, the system's complexity increase drastically, which imposes limitations on the device, like increasing in size and weight, limiting where the device can be used. Moreover, the cost and maintaining more complicated devices is more challenging.

Many walkers with STS assistance and walking aid are evaluated based on the Center of Pressure (CoP) displacement, the ratio of torque joints at the hips, ankles and knees, joint torques mean and maximum values, and the kinematics of the body. This can be done using motion capture systems and force plates.

To better understand how STS is approached from different point of view, we looked into wheelchairs with STS assistance, stationary devices with STS assistance and lower body exoskeletons [2] [3] [4][32]. Wheelchairs with STS assistance are preferred for people with severe paraplegic impairment, which is a great alternative since walkers only provide limited support in walking and standing up. Exoskeletons provide a great mobility aid for users with different levels of mobility impairments. Some exoskeletons provide walking aid and STS with different trajectories like "FB-AXO." [32], " TWIN" [4] and others [33] [34]. One of the exoskeletons' main limitations is the need for external assistance from someone to help a user wear or take off the device. Not having independence when doing daily tasks could negatively affect the users' mental health, as mentioned in the introduction of the thesis. Moreover, more work needs to happen on walking and STS trajectories to improve the users' experience and comfort.

We will look into the different types of devices we mentioned above in detail for the rest of the section to see how each type is designed; what actuators, sensors and test methods they used to understand better how different devices are evaluated.

2.1.1 Wearable devices

Matjačić et al. designed an STS training device shown in Fig. 2.1 [2]. This device can support multiple segments of the body, specifically the trunk, shanks, and thighs. The device can lift a body mass of 150 kg in a condition where the person is not assisting in the lifting. The device consists of a spring and actuator to perform the STS movement. The robot is designed to test the different levels of support and speed of the STS motion and to use it for rehabilitation and clinical use for neurologically impaired individuals. This device is not meant to be used as an everyday STS assistive device and does not provide mobility assistance. This device shows that as the level of support the device provides increases, the kinetics and EMG patterns decrease [2]. STS action using this device is divided into 3 phases, sitting position, ascending phase, and standing position, as shown in Fig.2.1. It is initiated by inclining the trunk and the shank segments forward with the thigh rotating in a counterclockwise direction. Then the trunk and shank segments will rotate in the opposite direction of their initial rotation until the user is standing. Supporting those body segments is necessary to generate unassisted biomechanics of STS transfer [2].

Figure 2.1: Stationary device that assist with STS (image taken from [2])

Khaled M. Goher designed an assistive device that provides STS support by tilting the the base frame (seat) and provide mobility support as well shown in Fig. 2.2 [3]. This is an actuated wheelchair that assist in STS movement and vice versa. The design consists of two linkages and a linear actuator on each side that are connected to the back support of the wheelchair [3]. When the linear actuators are active and extend, the wheelchair's seat and the linkages will change angles so the person's position will transform from sitting position to standing position. During STS, the seat belt has to fastened in order for the system to start the STS movement or stand to sit movement [3]. The device can be used for rehabilitation purposes with the back adjustment mechanism, as well as a mobility device without the need for external suppose [3]. The device is capable of supporting a weight of a 25 kg and can be controlled by the user to access different modes of the wheelchair [3].

Figure 2.2: A robotic wheelchair with STS assistance and walking aid (image taken from [3])

Laffranchi et al. developed a lower lib Exoskeleton (TWIN) that provides walking aid and STS assistance. The TWIN, shown in figure 2.3 is a wearable robot that helps users who need neuromotor rehabilitation and with locomotion and balance deficits following spinal injuries or strokes [4]. Twin consists of 4 motors mounted on the hip and knee on each leg. the device weighs 23 kg and can travel 1.5 km/h on patients weighing up to 110 kg. It has predefined trajectories the user can use for walking and standing up. The motion is initiated based on the IMU sensor reading that the TWIN has. Starting from a sitting position, it will autonomously stand up when the user tilts their trunk to a certain threshold. After standing up, the pitch and roll angles, defined as the waist's tilt, should pass a threshold value in order to take a step. The IMU sensor thresholds for standing and walking can be set according to the user's needs.

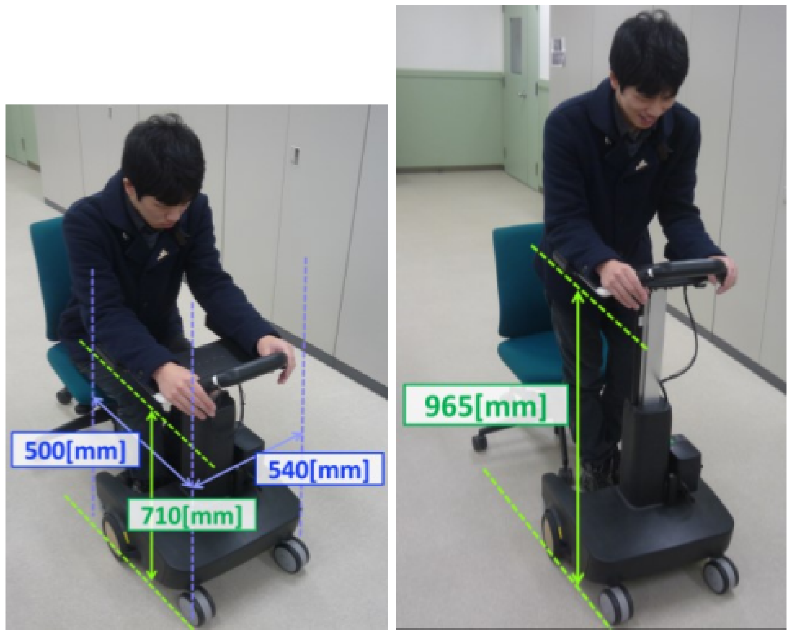
Figure 2.3: TWIN Lower Limb Exoskeleton (image taken from [4])

2.1.2 External devices

Yuk et al. developed a robotic walker that provides STS support, a walking aid, and an electric scooter [35]. The design consists of actuated wheels on the front and caster wheels on the back of the walker. It also consists of linear actuators for vertical movement for STS [35]. Strain gages are added to the handles to sense in which direction the force is applied to determine the motion. The users initiate STS movement by pushing the joystick buttons simultaneously to avoid unexpected initiation, and it takes 5 seconds to perform STS [35]. The maximum speed of walking aid is 2 km/h and 6 km/h for the electric scooter.

This paper presents a walker with sit-to-stand aid and walking assistance shown in Fig. 2.4 [5]. For STS movement, the user places their arm on a platform, and then a powered lift provides vertical force to raise the user. There are two steps of inputs the users have to do to stand up: 1. by detecting the user's hand and arm on the handles and armrest 2. the device guides the user to push on a switch on the handles, which initiates STS movement using a voice message. The force sensors inside the armrest pads and touch sensors on the handles allow the user to control when to perform STS. The voice control command is added to comfort the users by providing instructions on how to use it. It also recognizes when the user wants to perform STS movement using the sensors on the handles and armrest. The device does not provide support in the horizontal direction when standing up. The dimensions of the walker are chosen based on the Japanese industrial standard, which allows the walker to pass narrow doors like toilet doors [5]. In case of commercialization, it will come in different sizes according to the user's height. An actuated wheel on each with an electric brake is added to the walker for walking assistance. Caster wheels are added on the front, and the back of the walker for easy maneuverability [5]. Similar work has been developed in [36]; however, this walker is bigger than the one shown in Fig. 2.4 [5].

Saint-Bauzel et al. presented a robotic walker called MONIMAD shown in Fig. 2.5 [6]. MONIMAD is a mobile robot with actuated articulated arms with sensors-based control. The arm is a 2-degree freedom mechanism consisting of two linear actuators pulling and lifting the user. The handles stay horizontally at all times, which is achieved by combining two 1 degree of freedom in closed-loop mechanisms. The handles consist of a 6-axis force/torque sensor to measure the handling forces and 6 axis position sensor to measure the displacement of the hands. Using force sensors data, STS motion is divided into 4 phases: pre-acceleration, acceleration, start rising, and rising [6]. They developed a controller to identify the patient's stability and adjust the motion of the handle to the human voluntary movement [6]. The base of the walker consists of 6 actuators for driving and steering axis of the 3 wheels [37]. They use adapted control to initiate STS movement to give interactive ability between the user and the robot.



(a) Sitting position (b) Standing Position

Figure 2.4: A light weight robotic walker with 1 DOF for indoor environment (image taken from [5])

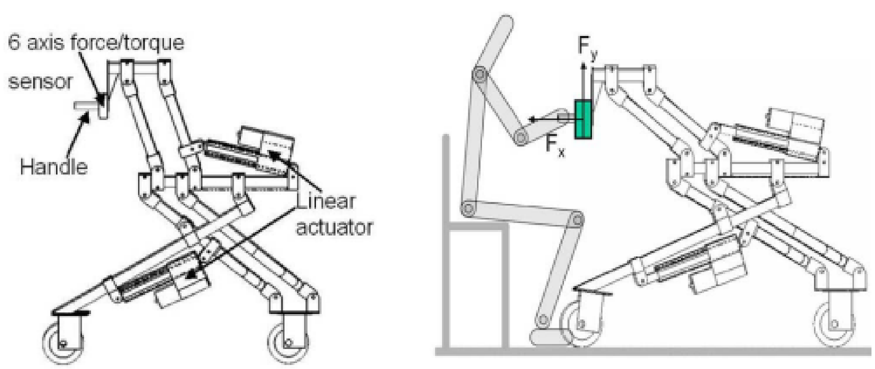


Figure 2.5: MONIMAD prototype (image taken form [6])

2.2 Passive devices

Passive devices usually offer a simple, lighter in weight, smaller size and lower cost. However, these device can not assist people with different level of support needed since the mechanism can not be adjusted for different STS trajectories or walking speed [7][8] [38]. Some devices only provide support in the vertical direction which is might harm the user as mentioned above [39]. Many designs consists with a gas spring to provide the lifting force and a harness that goes around the user for safety when lifting the user [40] [41] [9]. This require the assitance from another person and might cause discomfort to the user when the harness is still around them when they are walking.

Bulea and Triolo developed a passive robotic walker with STS assistance [7]. The walker consists of two gas springs on each side connected to a platform that can be raised. When standing up, the user's arm must be placed on the platform horizontally. Then the user pushes a button which will extend the gas spring and lift the user and platform up. When sitting, the user pushes a button and use the body weight to contract the gas springs [7]. The walker does not require a harness during STS.

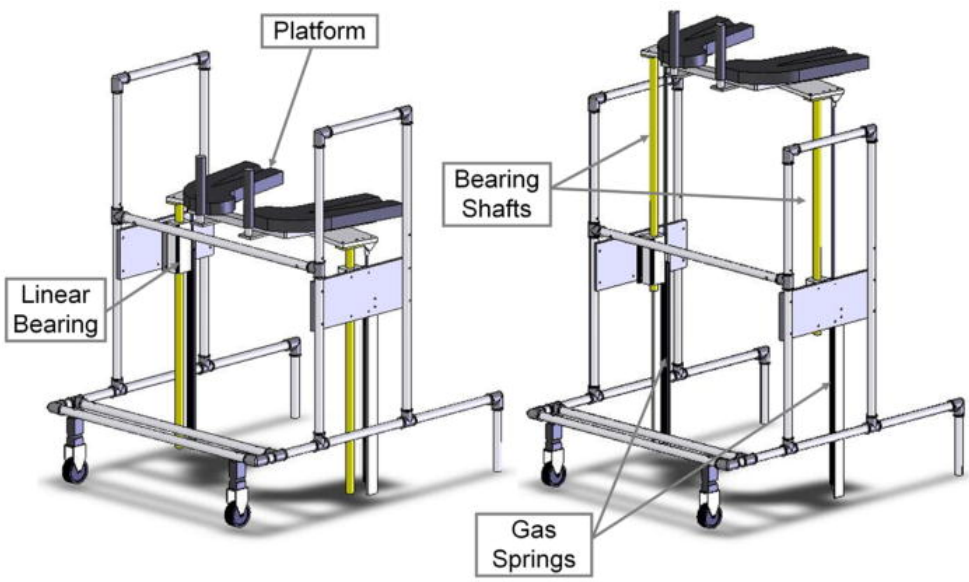


Figure 2.6: Two gas springs provide vertical support to lift the user (image is taken from[7])

Chang et al. developed a walker by redesigning a commercial standard walker by adding additional armrests, which help the user stand up shown in figure 2.7 [8]. The sit-to-stand movement has two stages: 1. users initiate STS by placing their hands on the new armrests and applying force to lift the body 2. transition from the lower handles to the upper level. The new armrests resulted in less time standing up and better satisfaction compared to the standard walker. Moreover, it resulted in higher peak-peak anterior-posterior acceleration, peak flexion acceleration and peak extension acceleration during STS [8].

(a) (b) (c)

Figure 2.7: "b type" armrest added on a commercial standard walker from different views (image is taken from [8])

Toride et al. presented a novel assistive walker with an STS mechanism for older adults with weak lower limb muscles[9]. The walker consists of a passive STS mechanism with a harness that goes around the user and is powered by gas springs that helps the body transition its center of mass during STS shown in figure 2.8. The torque provided can be adjusted based on the user preference and the amount of support needed. EMG results show a significant reduction in activation of the quadriceps, demonstrating that the walker provided support while standing up and setting down.

Figure 2.8: Walker with passive STS mechanism for older adults (image is taken from [9])

As discussed earlier, many assistive walkers can not function in indoor and outdoor environments or small areas because of their size, weight, or complexity, which does not give the user the mobility they require to perform their basic tasks/needs independently. Many active devices can only be used in the clinical setting as they are complex, heavy, and costly to make and maintain. However, they provide a greater amount of support compared to passive devices. Many passive devices require a tool like a harness around the user when standing up. This method could not be comfortable for the user and requires the user to use their body weight to bring the lift down when sitting. Passive devices do not generate different STS paths to accommodate different users, and the speed of STS action and walking cannot be controlled.

Chapter 3

Design Consideration

It is recommended that people, in general, need to walk/perform physical activities for 30 minutes a day, five days a week [1]. Based on Statistics Canada, men and women aged 65 and older spend time on active pursuits on average of 3.6 and 3.5 hours, respectively [2]. A walker that can operate both indoor and outdoor environments is essential because it will give the user flexibility during use. Average door sizes for rooms, bathrooms, and house entrances [3] influenced the dimensions, type of wheels, and the weight of the walker. Additional details are discussed in the mechanical systems section.

For STS movements, geriatric clinicians recommend that the user's arms should be vertically straight down so that support is transmitted through the stretched arms with a lifting force applied on the hand; lifting assistance can help carry the person's weight up from a sitting position with the help of the (reduced) lower limb efforts. The lifting design was built based on this consideration.

Another recommendation that is sometimes given for STS support in the elderly is to not bring them up to a fully standing position in one move, but first to a halfway pose with stretched legs, then bringing the torso to an upright position.

In individuals, the lower body is significant in providing force and stability when standing up [42]. However, it is important for individuals who lack lower body strength to be assisted while standing. The walker prototype will assist 25 % to 30 % of the average body weight of an older adult, as the goal is to give the user the necessary force to perform STS. It is not recommended to support a higher body weight ratio while standing up since an

[1] www.fgblawfirm.com/blog/2018/june/recommended-walking-distances-for-seniors/

[2] www150.statcan.gc.ca/n1/pub/75-006-x/2018001/article/54947-eng.htm

[3] www.doornmore.com/help/what-is-the-standard-size-for-residential-homes.html

older adult who needs assistance equivalent to more than 30 % of their body weight will have difficulties walking on their own and actively holding onto the handles of the robotic rollator.

In this Chapter, we will go over the thesis objective and the requirements needed to achieve the thesis goal. The biomechanics of the Sit-to-Stand (STS) movement will be discussed, how different researchers define the task of (STS) and the requirements to achieve a healthy STS. They are followed by examining biomechanics and requirements for healthy walking. These evaluations are used to design a safe and easy-to-use robotic walker. Finally, an overview of the design solution will be discussed.

3.1 Need Statement and thesis objective

A need exists to assist older adult with mobility impairment, specifically with poor STS performance, to stand up, sit down and walk safely.

The objective of the thesis is to build a novel lightweight device that can help users have the ability to stand-up from a sitting position in different environments and have the ability and encourage walking in an indoor and outdoor environments.

In order to have a proper design process and determine which requirements are needed compared to others, functional, non-functional and constraint requirements have been chosen and evaluated. The following requirements are essential to have in order to have a successful design :

1. The design must be safe to use
2. The design must be easy to use
3. The design can be used in indoor and outdoor settings
4. Good maneuverability

5. The design should be easy to transport
6. The device should not limit the user's movement while rising
7. The device dimensions within the commercial average
8. The device should be simple and easy to manufacture
9. The device can be used with users of different widths and height
10. The device can generate different STS trajectories
11. Cost

3.2 Sit to Stand Movement

3.2.1 Determinants of the Sit-to-Stand Movement

Chair Determinants

Previous work have indicated that the chair influences how well STS movement is peformed. The work looked into seat height, armrest position, chair type and backrests [43]. Seat height of the chair can change the biomechanical demands and/or can change the strategy to stand up [43]. Schenkman et al. show that lowering the height of the seat is physically more demanding to stand up and can even lead to unsuccessful STS movment [11]. With a lower seat position, the hip angular velocity is increased, re-positioning of the feet " stabilization strategy" is necessary in order to stand up for older adults [44]. For healthy young adults, lowering the seat from 115 % to 65 % of knee length increased the angular velocity of the trunk flexion to almost 100% [11]. Moreover, different seat heights show change in the moments needed at the hip and knee to stand up, with greater influence on the knee [45]. The angular displacement for the trunk, knee and ankle increases with lower seat heights [46]. Weiner et al. showed that the minimum seat height to have a successful STS movement for older adults with difficulties standing up should be 120% of lower leg length (knee to ankle distance) [47].

When using the chair's armrest, it results in lower moments at the knee and hip. Arborelius et al. compared 4 different types of stools with armrest, they concluded that when using arms to stand up reduced the mean maximum hip moment by 50% [48]. However, no difference observed on joint angles when using arms to stand up [48]. Alexander et al found no differences in body segments rotations when using arms for healthy young adults [49]. When using arms to stand up, the older adults who are unable to rise without the use of armrests compared to older adult who can rise took more time to perform STS and used different body segment rotations and larger force to accomplish the task [49].

Sit-to-Stand Movement speed

The total time of STS movement in an important variable to consider when evaluating a STS trajectory. Vander Linden et al. shows that different speeds have no influence on the joint angles [50]. Pai et al. did an experiment with healthy adults and performed STS at different speeds [51]. They showed that when the rise speed is increased, the hip flexion, knee extension, and ankle dorsiflexion joint moments are increased. Moreover, they showed that faster STS movement has an effect on the peak vertical momentum of the center of mass while peak horizontal momentum does not change. Finally, Gross et al. older adults between 64-84 years old were not as successful in increasing their STS movement speed compare to younger adults [52].

Foot positioning

Shepherd et al. showed that placing the feet more posterior will shorten the amount of time it takes to perform STS movement [53]. This resulted in decrease of hip flexion and hip flexion speeds. Kawagoe et al. performed a study with multiple chairs heights and with anterior, vertical, and posterior foot placement. Ten healthy adults male participated in the study, with a mean age of 30.2 years, mean height of 172.0 cm and mean body weight of 71.9 kg. They observed synchronous and long-sustained activity of the muscles in order to shift the body's center of gravity forward before and after lift-off from chair [54]. Also, they concluded that when positioning the feet posteriorly resulted in lower maximum mean extension moments at the hip from 148.8 Nm to 32.7 Nm compare to anterior foot placement when performing STS momvement [54]. Aller et al. presented a benchmark using a humanoid robot and found that chair height and ankle-to-chair distance are important indicators to asses overall STS performance [55].

Arm support

Wheeler et al. studied the affect of performing STS movement using armchair between younger adults ($\overline{\mathrm{X}} = 24$) and older adults ($\overline{\mathrm{X}} = 75$). They concluded that older adults and even younger adults commonly use the armchair to stand up [56]. Janet H. Carr found that the body's center of mass is influenced based on arms position [57]. When the arm movement is restricted, the momentum and position of the center of mass are affected, which affects the pattern of ankle joint displacement in the extension phase [57].

Knee position

Fleckenstein et al. found that positioning your knee in more extension position resulted in greater hip extension moments by 77 % and an increase in hip joint angular displacement [58].

3.2.2 Biomechanics of Sit-To-Stand

In order to be able to do physical and daily activities with independence, persons with disability need to be able perform the sit-to-stand (STS) transfer, which are one of the most performed activity throughout the day [18]. The inability to perform this activity could lead to impaired muscle functions and mobility in daily activities, and death [59] [60]. To perform healthy and safe STS motion, it requires adequate muscle strength to shift the body's center of mass upward over the base of support during the movement. Roebroeck et al. show that the forward rotation of the upper body helped generate the velocity of the center of mass in the horizontal direction, while the the extension of the legs generated the velocity in the vertical direction [10].

Moreover, researchers were able to identify multiple phases of STS motion. To identify those phases, they collected kinematic data for joints and body segments, kinetic data for evaluating ground reaction forces (GRF) and muscles activity during STS task [10] [61].

The lower body and trunk muscles play important rule body balance during STS motion. Different studies looked into different muscles when evaluating muscles activity during STS, since the muscles used depend on how the subjects are standing up [62] [63] [64]. Lower body muscles for STS are gastrocnemius (GAST), quadriceps, biceps femoris (BF), rectus femoris (RF), soleus (SO), tibialis anterior (TA). Jiménez et al, looked into muscle activity and fatigue during different repetitions and speeds for STS motion for upper and lower body muscles. The results show an increase in muscle activation (for medial gastrocnemius, BF, and erector spinae) when increasing repetitions, while showed significant difference in MVC percentage in the upper body muscles for abdominal rectus, erector spinae [64]. Moreover, previous worked did not only look at which muscles contribute to standing up, they identified which muscles contribute more in certain phase of STS compare to other muscles. Millington et al. described the 3 phases from the sagittal kinematic data collected [61]. Phase 1 of STS motion, shows that erector spinae was the first muscle activated. At the end of phase 1, vastus medialis, (RF) and thigh muscles show activity for the knee extension. In phase 2, all muscle group (mentioned in the paper) were active until full standing up.

3.2.3 Sit-To-Stand Phases

This section looks into the most commonly used STS phases in literature. We looked at the definition by Roebroeck et al., which distinguishes STS by 3 phases shown in figure 3.1 and Schenkman et al., which distinguishes STS by 4 phases shown in figure 3.3. Those two definitions are very similar, however, Schenkman et al. describe the ankle joint state in phases 2 and 3 while Roebroeck et al. did not, and he introduced a stabilization phase at the end. Phase 4 is essential to consider when developing our definition of STS phases for safety since the user is still in motion and may fall before fully standing up. This comparison helped us develop our definition of STS shown in figure 3.5. We developed 3 unique phases when using our device: 1. Sitting phase, 2. lifting phase (forward momentum generation phase and ascending simultaneously), 3. handles switching phase.

Roebroeck et al. divided the STS motion to the following: phase 1, weight shift; phase 2, transition; and phase 3, lift [10].

The first phase involves shifting the body weight forward by trunk flexion until the knee extension was initiated.

Phase 2 involves the transition from shifting body weight to lifting the body upwards. This results from knee extension and initiation of the reversal of trunk flexion from phase 1 to trunk extension.

Finally, phase 3 involved full extension of the trunk which will results in standing position as shown in Fig. 3.1.

Schenkman et al. definition of the phases is used more frequently which is divided into 4 phases [11].

Phase 1 (flexion-momentum) the motion of STS in initiated and the phase ends just before the buttocks is lifted from the seat of the chair. This phase involves the trunk and pelvis rotation forward into flexion.

Phase 2 (Momentum-transfer) starts with buttocks being lifted from the seat and the phase ends with the maximum ankle dorsiflexion. The maximum trunk flexion, hip flexion

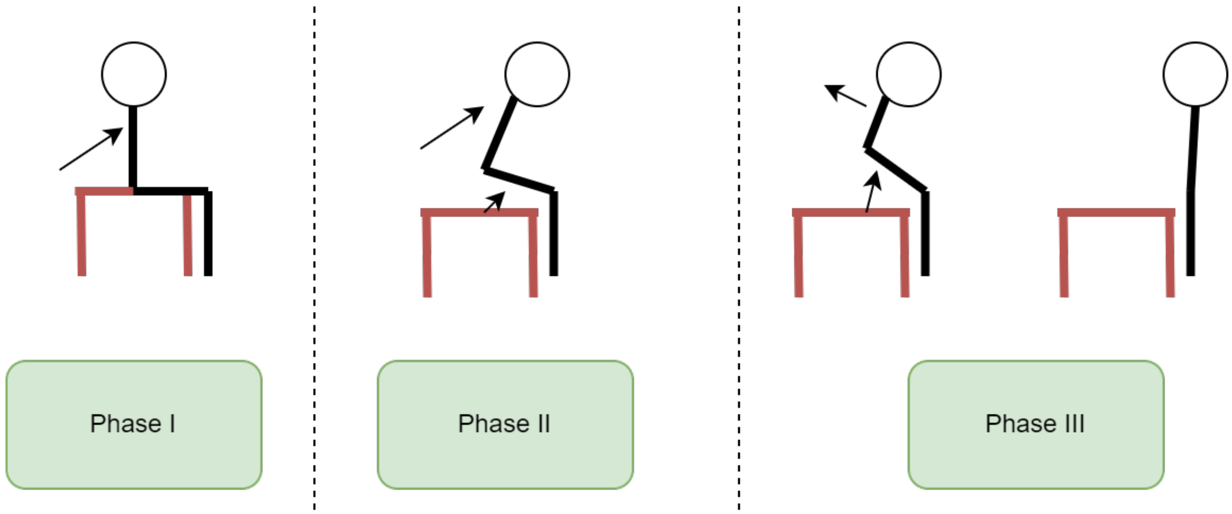


Figure 3.1: Three phases of STS motion as defined in [10]

and head extension is also reached. The differences between the right and left side of the body were not significant at the hip, knee, or ankle.

Phase 3 (extension) is initiated just after maximal ankle dorsiflexion and the phase ends when the hip first ceased to extend. the period of this phase depends on the time at which the hip-extension velocity reaches zero.

Phase 4 (stabilization) starts when the hip-extension velocity is zero and continue until the motion associated with stabilization from rising is complete.

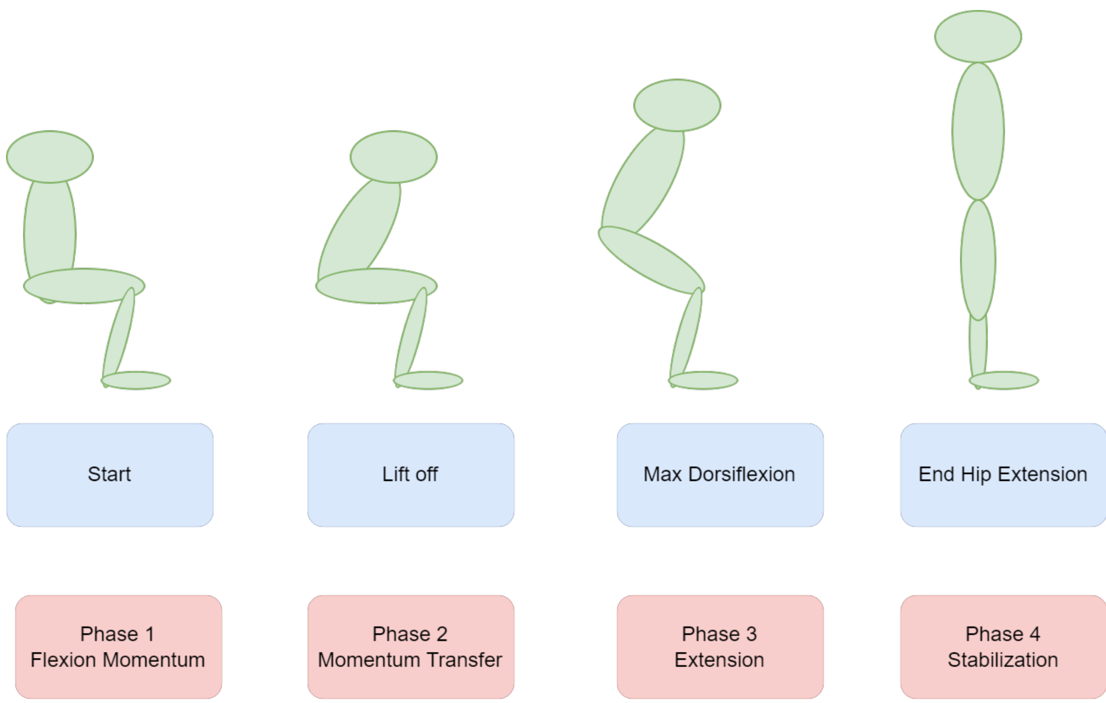


Figure 3.2: Four phases of STS motion as defined in [11]

3.3 Walking

Since mobility disabilities are the most common disability type, affecting 1 in 10 Canadian adults, understanding the biomechanics of walking is essential when designing the walker to assist older adults effectively. The most common risks for mobility impairment are Vascular, Neurological and Orthopaedic disorders. Pirker and Katzenschlager show that gait and balance disorders are 10 % in people between 60 to 69 years and 60 % over the age of 80 years [12]. Gait disorders lead to falls, injuries and reduced quality of life. Walking speed is correlated with the individual life expectancy in older adults [65]. The average walking speed for adults up to the age of 59 years is 1.4 m/s. The Average stride lengths (linear distance covered by one gait cycle) in healthy adults range between 150 and 170 cm. Ageing is correlated with the decline in gait speed and step length, while cadence (number of steps per unit of time) remains relatively the same. The preferred walking speed for older adults with age over 80 years is 0.95 m/s [66], and the step width in older adults is 40 % wider compared to young adults, with an average step width in older women around 8 cm and older men 10 cm [67]. Keeping those parameters in mind, we designed SkyWalker to have a healthy gait cycle for older adults by adjusting the walking speed and the height of the walker handles.

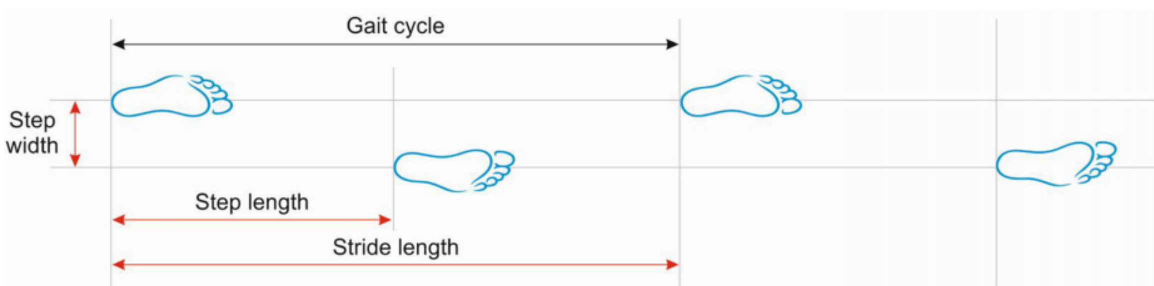


Figure 3.3: Gait cycle terminology (image taken from [12])

3.4 Design solution overview

Based on the state-of-the-art review of the assistive devices, biomechanical evaluation of STS and walking, recommendations from geriatric clinicians and elderly experts and evaluation of the functional and constraints requirements, the robot SkyWalker was designed. The robotic walker consists of two mechanisms that provide horizontal and vertical support during STS action. To initiate STS motion from a sitting position, users place their hands vertically down, as shown in figure 3.5. The width of the lower-level and upper-level handles were adjusted based on the user's body size, height, and preference, which included adjusting the height of the upper-level handles as well. The initial height of the lower-level handle was fixed for all subjects. Users can place their feet in any position based on their preference before initiating STS action. The STS movement starts lifting the user by simultaneously providing vertical support using the vertical lift and horizontal support from forward motion by moving the chassis for a specific distance shown in figure 3.5. The users can initiate the desired action using voice control using Alexa by giving voice commands of the desired action to the robotic walker.

Figure 3.4: SkyWalker design with shell to hide electronics and motors

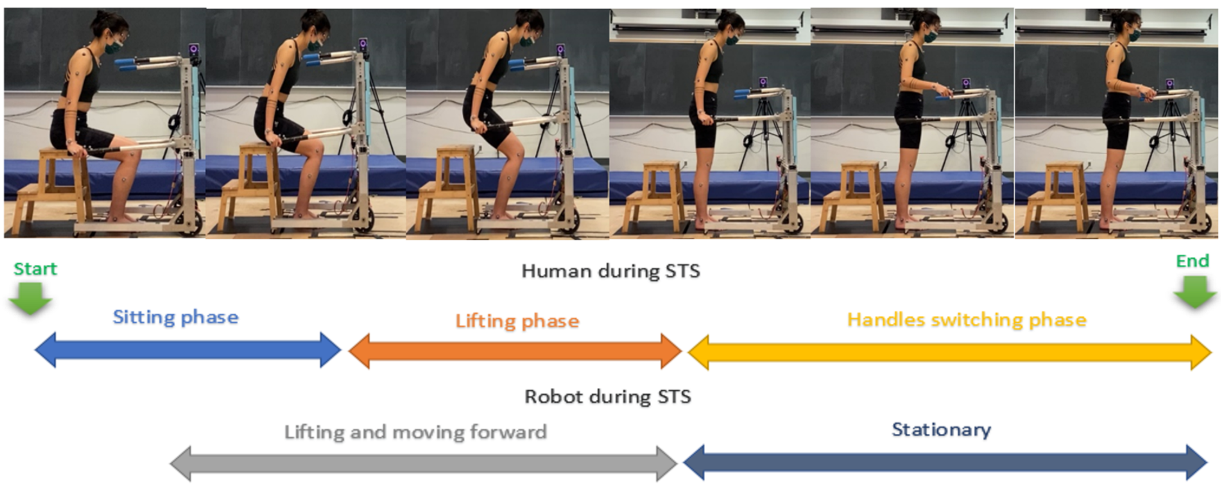


Figure 3.5: Image sequence demonstrating STS assistance by the SkyWalker. The arrows indicate the different phases of the motion: For the human (first line) 1. sitting, 2. lifting up through support of lower handles, 3. switching from lower to upper handles: for the robot (second line): 1. starts lifting lower handles and simultaneously driving forward while the human is still sitting, until the endpoint is reached, 2. waits at rest while human re-grasps. Note that the initial height of the lower-level handle depends on the chair height. For details, please see the supplementary video.

Chapter 4

SkyWalker

In this chapter, we will cover previous prototypes and technical details of the SkyWalker. Moreover, the aesthetics choices of the shell design that hides the electronics and the walker's colors will be discussed.

4.1 Development Process

As mentioned in section 3.4, the walker is designed based on multiple and different considerations since the walker has to to assist in walking and STS action.[1] To overcome this challenge, rigorous prototyping and constant feedback while designing made designing SkyWalker easier and faster. Figure 4.1 shows the development stages of SkyWalker and the main changes implemented in the design at every stage. After finalizing the robot design, we started working on software of the robot which focused on generating different STS trajectories at different forward travel distances and speeds. Finally, we added voice command feature using Alexa so users can have communicate with the walker to perform desired action.

[1]This is a video that shows how SkyWalker works: https://youtu.be/XTzNcISHy2U

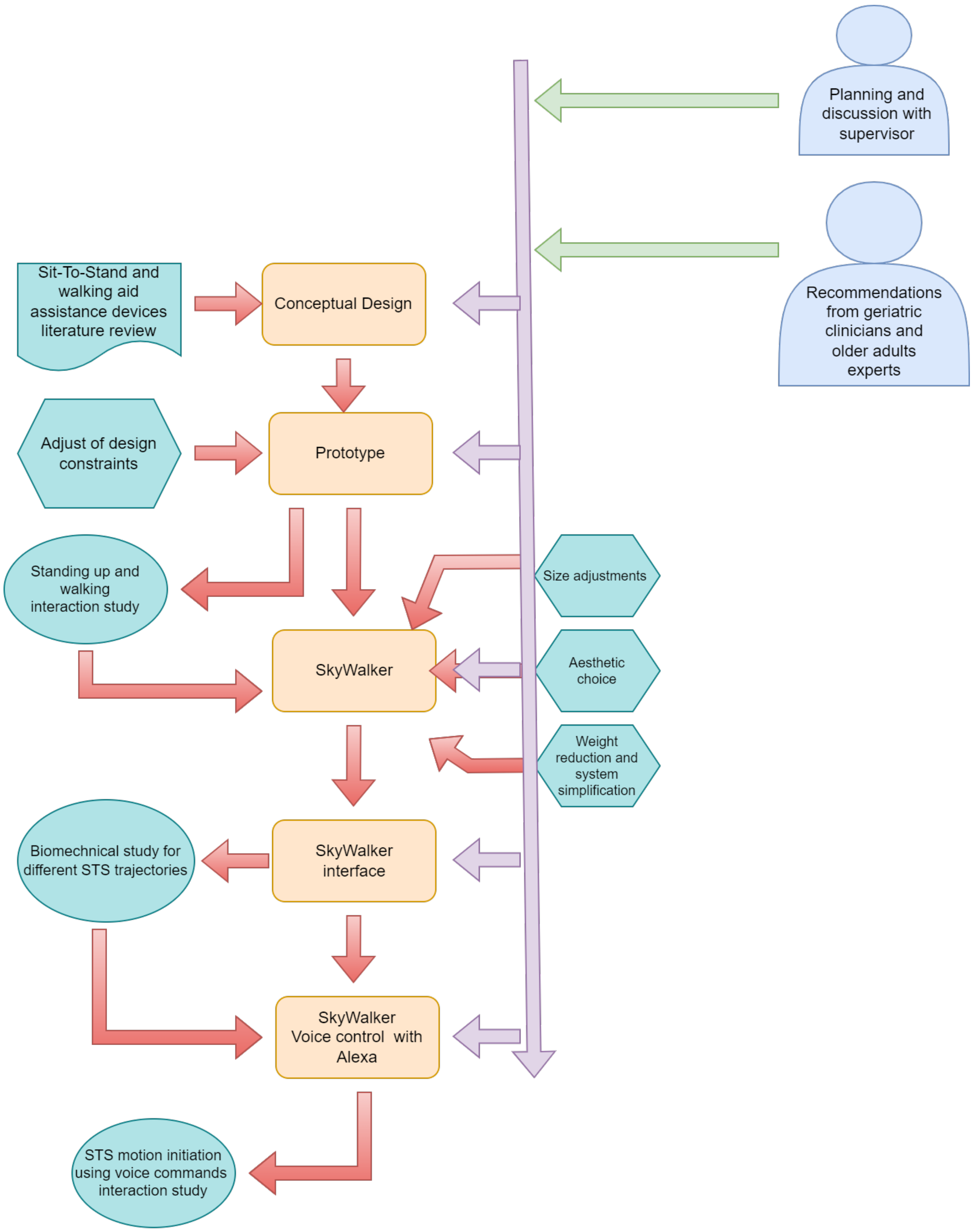


Figure 4.1: Development stages of SkyWallker and the main factors influencing design choices at each stage

4.2 Robot Concepts

Many concepts have been designed on CAD software for a mechanism that provide the necessary force that will raise the user from their setting position in a healthy and safe way. Active and passive lifting mechanisms were considered when designing the robotic walker. The active mechanism has motors controlled by an electrical system, while the passive mechanism does not have a system powered by a battery.

Looking back at our need statement: **A need exists to assist older adults to stand-up and walk safely**, it is essential to have a walker with the capability to operate in indoor and outdoor environments and able to perform STS action.

4.2.1 Conceptual Design

In one of the concepts that have been built and tested, we decided to use a passive lifting mechanism and motorized chassis for walking assistance. The concept design of the chassis had the ability for rear wheels to be extended during STS motion, so the rollator does not tip over due to center of mass shifts, as shown in figure 4.3. The back wheel is a caster wheel for easy maneuvering while using it. The extension mechanism aims to prevent the tipping of the robotic walker when the user is trying to stand up. The extension mechanism can extend up to 15 cm. The height of the extension mechanism should not be more than 6 cm because the mechanism should go under as many chairs/couches as possible. We came to this conclusion after looking at the average leg height of the furniture. The extension mechanism consists of a linear rail and linear sliders for horizontal translation movement, powered by a linear actuator shown in figure 4.2.

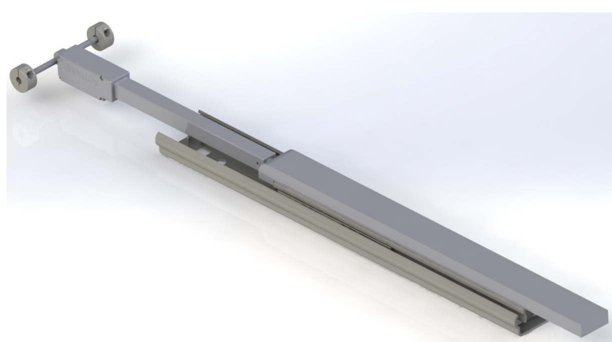


Figure 4.2: extension mechanism components

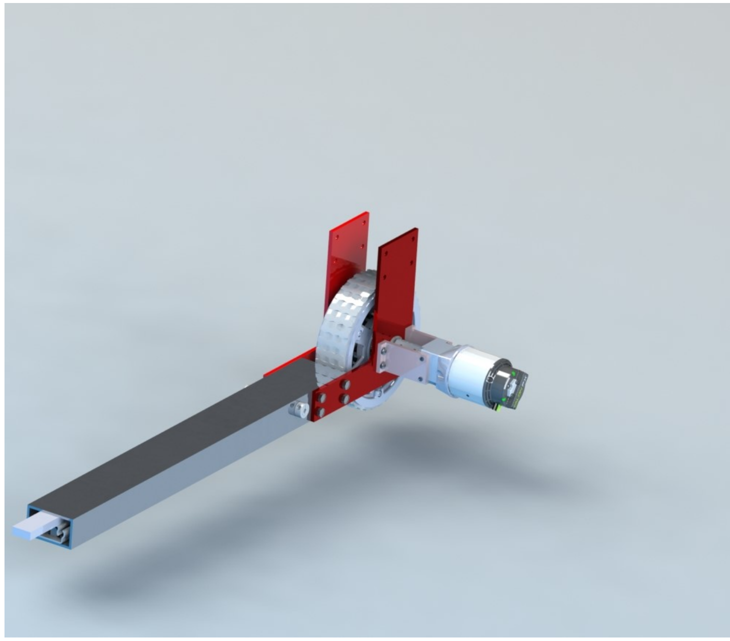


Figure 4.3: Chassis design with extension mechanism

For the lift mechanism we considered adding a gas spring to a 4-bar linkage with springs shown in figure 4.4. The 4-bar linkage is chosen since the end-effecter (handles) of the system will stay parallel at all times during the STS movement. The lifting action starts when the lock on the gas spring is released, which will cause the linkage to rise. However, the user must use their weight to bring the handles down. This is an issue because if the user does not stand up when the mechanism is released, they will not be able to bring the lift down since they need their body weight to bring it down. This problem can be solved by adding another gas spring to bring the handles down, but this approach will bring more weight, complexity and cost to the walker. Also, in terms of mechanical design, manufacturing the linkage is expensive and maintaining the system over time will be hard. One of our main constraints which is related to the safety of the user **The device should not limit the user's movement while rising**, so we could not add a harness or something that can go around a body part. Moreover, we added an extra design requirement **The device can generate different STS trajectories**. In passive mechanisms, the system will get more complicated if we want to generate different type of trajectories for Sit-To-Stand and Stand-To-Sit actions.

(a) front view

(b) Side view of the lift mechanism

Figure 4.4: Linkage mechanism

4.2.2 Prototype Design

In the prototype, many major changes have been applied. The chassis has been simplified, lighter in weight and structurally stronger. The lift mechanism changed from passive to active mechanism. The extension mechanism was not implemented for the chassis because the robotic walker design is modified so it does not tip over when the user is applying the load on the handles when standing up. The red plates shown in 4.3 have been replaced with a lighter and stronger gusset design shown in figure 4.5. More details about the motor choice and specification will be discussed in the electrical section of the thesis. Weight and cost are issues with this prototype since we are introducing an entire electrical system we did not have in the passive concept design.

On the other hand, considering the electrical system in the early stages of design allows for better integration of sensors and other electrical devices later to improve the user-robot interaction. Moreover, one of the main constraints is met, which is the ability to generate different trajectories for STS. The lift mechanism chosen for the second prototype consists of a custom build Stepper motor-controlled lead screws system shown in figure 4.8. A lead screws drive mechanism converts rotary to linear motion. The mechanism is designed to be rigid and suitable for our particular application. The end of the lead screw in the mechanism is Fixed-floating (or fixed-simple) which provides axial and radial support for the screw and contribute to high critical speeds and buckling loads [2]. Also, it is important to avoid buckling(compressive) load, which might lead the screw to bend. The following equation is used to determine the buckling load:

$$F_c = f_b \cdot \left(\frac{d_1^4}{L^2}\right) \cdot 10^4$$

where: $\mathrm{F_c}$ = maximum compressive load (N) f_b = end bearing factor $\mathrm{d_1}$ = root diameter of screw (mm) L = unsupported length (mm)

The f_b can be controlled based on the type of support bearings in the mechanisms. As mentioned earlier, we are using fixed-simple arrangement which results bearing factor to approximately $f_b = 2.5$. Moreover, mounting the screw assembly with the fixed bearing at the top put the screw in tension rather than compression and counters the effects of the axial load 4.8. This is necessary to avoid excess compressive forces on the screw. Also its important to calculate the critical speed the system can handle, because if it exceeds the limits (which can be get from the manufacturer) it might cause severe vibration and noise which can damage the screw assembly system. The following equation is used to calculate the critical speed:

$$n_c = f_c \left(\frac{d_r}{L_c^2}\right) x10^7 \left(\ \mathrm{min}^{-1}\right)$$

n_c = critical speed (rpm) f_C = factor based on end support bearings d_r = root diameter of screw (mm) L_c = unsupported length of screw (mm)

Finally, the screw is self-locking meaning that the screw cannot be turned by the axial force. It does not need a brake or constant power supply to hold the load in its place which is very important for our application.

The second prototype concept was determined to be the most suitable for our challenge and which is what is used for the SkyWalker design. However, many changes have been applied to SkyWalker. The walker dimensions have changed by increasing the walker's overall height and reducing the width of the walker. The stepper motor for the lift has

[2]https://www.linearmotiontips.com/how-to-avoid-ball-screw-buckling/

been changed to a brushless motor; it will be discussed in detail why the change was needed in the next section. Finally, SkyWalker is lighter in weight and has a shell to hide electronics from users.

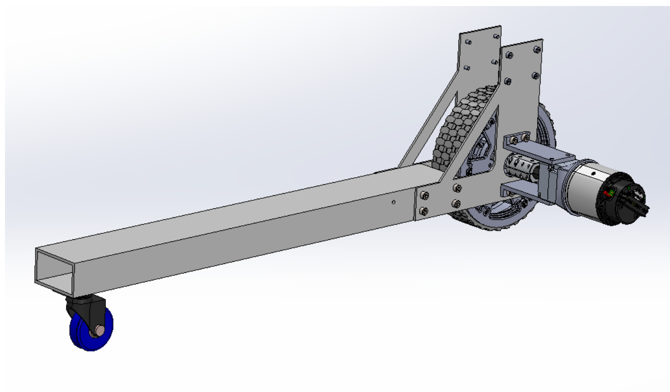
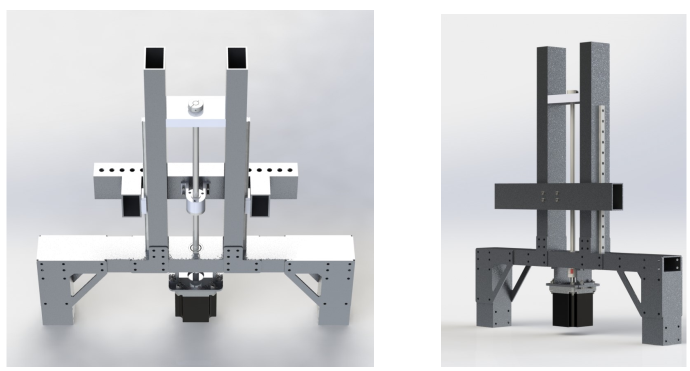


Figure 4.5: extension mechanism components



(a) (b)

Figure 4.6: Image of Lead screw lift mechanism in CAD software (a)Back view of the lead screw lift mechanism. (b) Front,side view of the lead screw lift mechanism

4.3 SkyWalker Design

The design criteria were chosen based on an in-depth literature review of previous designs for STS assistive devices, assistive guidelines used by caretakers and professional consultants, and size & cost constraints. The design provides forward motion and vertical assistance at the same time during STS movement. As shown in figure 4.9, the design consists of two arm handles at different heights. The lower arm handles are motorized and will provide vertical lift assistance during STS motion. The upper-level handles are stationary and are used to support the user during walking. Users must actively switch from the lower to the upper level handles one hand at a time and at their own pace after reaching the highest point the lower handles can reach.

For the rollator chassis, the front wheels are motorized, which provide forward motion during STS motion, while the rear caster wheels are smaller for easy maneuverability. The modelling software Solidworks was used to conceptualize the robot. This allowed us to test how each part and mechanism will react when forces are applied by observing the stress, displacement, and strain, given predetermined factors of safety. The minimum factor of safety was 3. Figure 4.7 shows a visualization of where most of the stress is happening on the walker when a load is applied on the handles when performing STS. The SkyWalker's dimensions are shown in figure 4.9. The weight of SkyWalker is 19.6 kg with electronics and a battery.

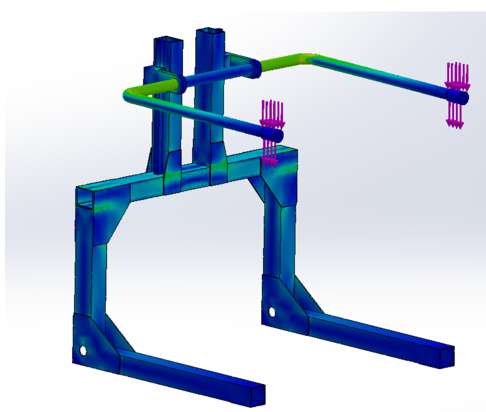
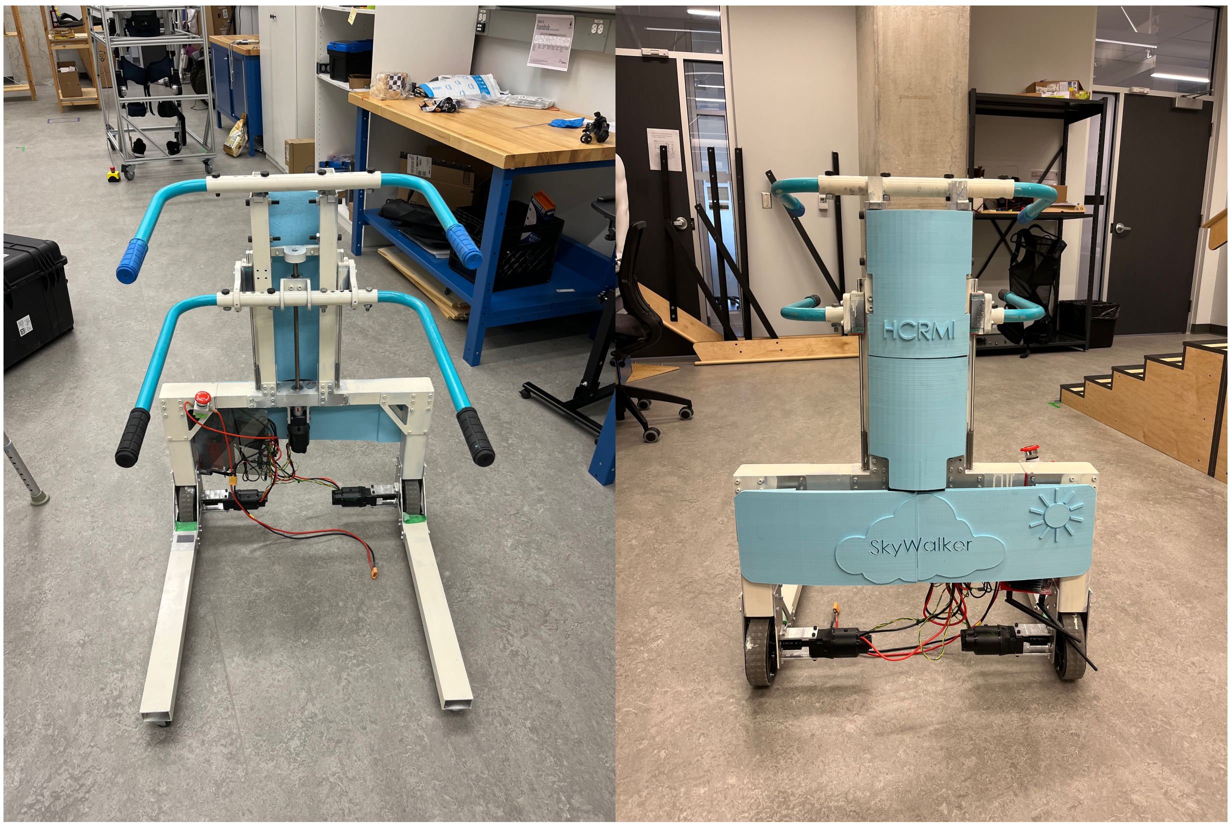


Figure 4.7: Visualization of where most of the stress when lifting the user. Lower stress area are shown in blue, and higher stress area are shown in green. 800 N have been applied on the handles for this visualization (three times more load than the intended use on the walker)



(a) Back view of SkyWalker

(b) Front view of SkyWalker

Figure 4.8: Final design of SkyWalker, painted and with the old shell design. The electronics on the back are shown without the shell covering them.

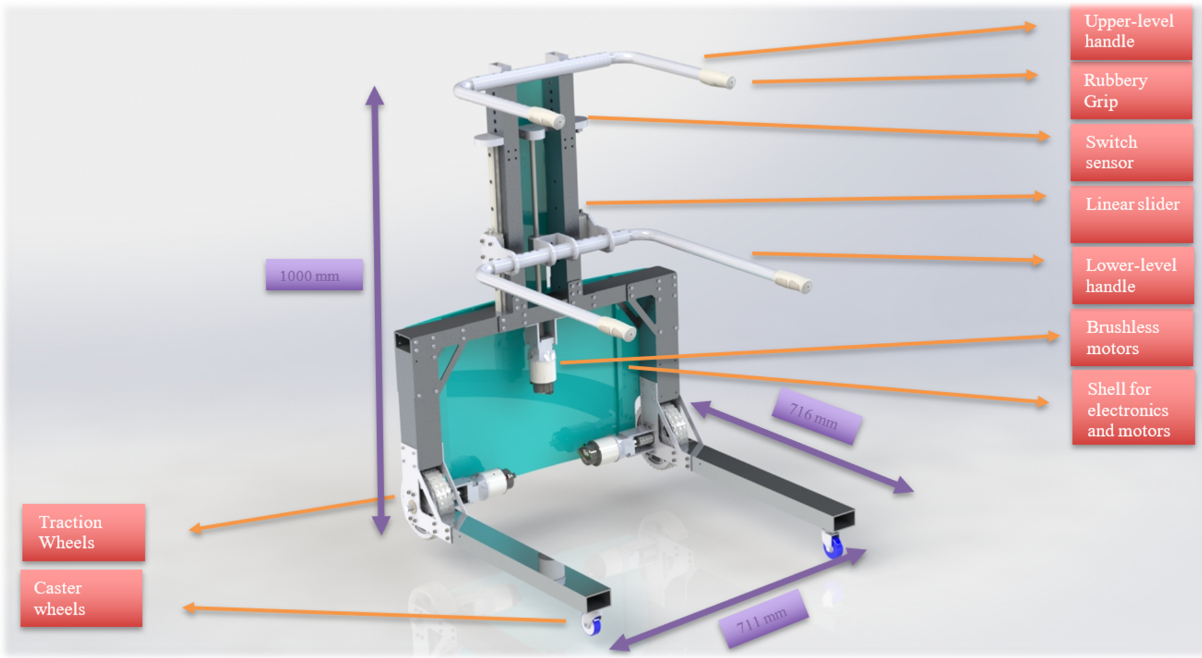


Figure 4.9: CAD model of the mechanical design of SkyWalker and break down of its components

4.3.1 Chassis

As shown in figure 4.9, the chassis consists of motorized stationary wheels at the front of the walker and passive caster wheels at the rear. The front wheels are 152.4 mm (6 inches) in diameter and 38.1 mm (1.5 inches) wide. The wheels are made of glass-filled Nylon, and the tires are made of rubber with a fiberglass reinforced base for high traction on the ground. The size of the front wheel is chosen, so the rear wheel height is no more than 60 mm; more details about the rear wheels are in the next paragraph. The shaft of the front wheels is 12.7 mm (0.5 inch) and connects to the motor using a shaft coupler. The body of the chassis is made of an Aluminum 6061T6 rectangular tube which provides a lightweight design and high strength. The Aluminum tube was cut to the correct length and assembled together. Custom designed gussets are used to connect the chassis to the load bearing structure.

4.3.2 Lift mechanism

The lifting mechanism is responsible for providing the vertical force during STS the person from a sitting position. The lift mechanism consists of a lead screw connected to a brushless motor using a motor coupler. The brushless motor is mounted to the horizontal aluminum tube. The linear rails are mounted on the two vertical aluminum tubes around the lead screw, which will guide the lower handle up. The handle mount is connected to linear sliders that go on the linear rails, as shown in figure 4.9. The minimum initial height of the lower arm handles is 39 cm is set to meet ergonomic and safety constraints characterized by the average heights of chairs and users. However, this initial height can be changed depending on the chair height and the user's preference. The lower arm handles can travel 300 mm vertically in the sagittal plane. After the lower handles travel to the required distance and completely stop, the user places their hands on the upper handles to transition to a fully standing position as shown in figure 3.5.

The initial distance between the handles is based on the average shoulder width of the elderly population, which ranges from 336–463 mm [68] [3] [4]. The initial distance between the handles is shown in figure 4.10. However, the distance between the handles can extend up to 20 cm to cover a wider range, depending on body size. In figure 4.10, the model shows the handle mount tube that has holes, whereas the handle tube has the same holes so the handle mount tube can slide in and out of the mount tube. Aligning the holes on the handle tube and mount tube will determine the distance between the handles. The initial height of the upper-level handles is chosen, so the height of the handles should be on the same level as the hip joint with consideration of the wrist and elbow angles [69]. Also, commercial rollators were considered when choosing the initial height of the upper-lever handles. The minimum height of the upper-level handles is 100 cm and be raised by 10 cm depending on the user's height and preference.

[3] www.healthline.com/health/average-shoulder-width

[4] www.firstinarchitecture.co.uk/metric-data-01-average-dimensions-of-person-standing/

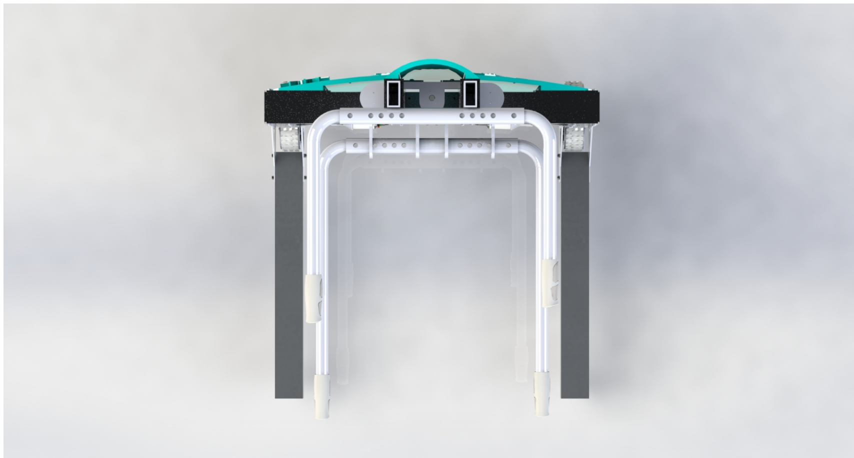
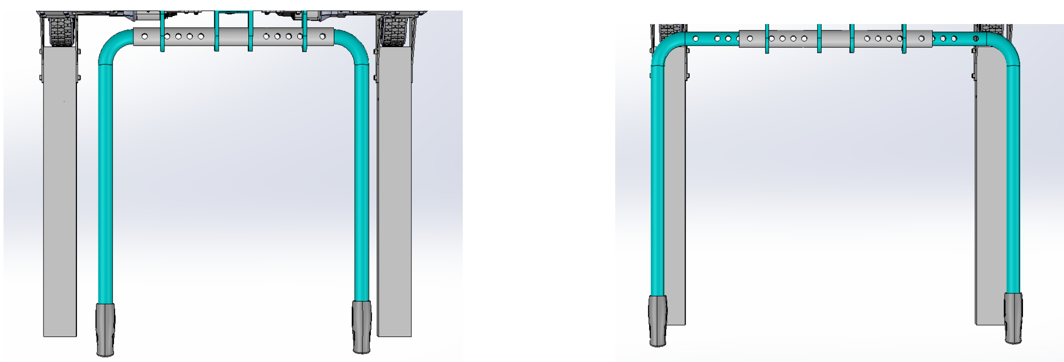
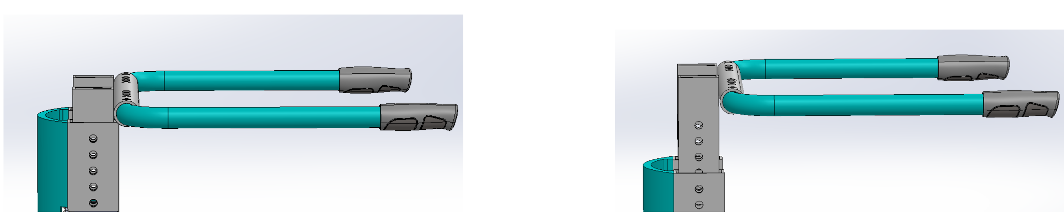


Figure 4.10: A bird's-eye view of SkyWalker with narrow handles width



(a) Narrow configuration of the lower handles (b) Wide configuration of the lower handles



(c) Low configuration of the upper handles (d) High configuration of the upper handles

Figure 4.11: Different position configuration for the lower and upper handle positions. The configuration can be changed by inserting bolts into different holes. The handle's width in (b) is wider by 20 cm than (a). The height in (d) is greater by 10 cm than (c)

4.4 Electrical System

Safety is one of the significant constraints in our system. The control system is designed to be safe and straightforward and relies on commercially available components. The system uses a lithium polymer battery with a fused power board to ensure SkyWalker does not harm the user and damage the electronics. We have also implemented safety features into the software; an S-curve velocity profile was used to ensure smooth motion by minimizing jerk and reducing oscillation of the mechanism, resulting in a more controlled and reproducible trajectory. Moreover, one of the features we added to the walker is voice control using Echo Dot (3rd Gen) Smart Speaker with Alexa. In this section, we will discuss the hardware system; their iterations what we currently using on the walker.

4.4.1 Hardware

The goal when designing the hardware system is to be safe, reliable, lightweight, cheap and use the minimum amount yet commercially available components. Our first design is shown in figure 4.12. The system consists of brushless DC motors with a step-down gearbox ratio 10:1 for the chassis, linear actuators for the back extension mechanism, and a stepper motor for the lift mechanism. We use a nvidia jetson nano and an Arduino for the computing units. Finally, we are using two lipo batteries in our system, one battery for the lift mechanism and the other battery for the rest of the walker. This is done because we wanted to have the lift system independent and can be operated even when other systems fail. A power board is used to motors and computing units.

Code can be deployed to the jetson nano over wireless networking using SSH. Since the system does not have any features or sensors to allow the user to control walking directions and speed, a joystick is used to control the walker's movement. An operator controls the movement and communicates with the user, so they know what the following action will be. More details on how the robotic walker moves will be discussed in the next chapter.

Figure 4.12 shows how the power and communication protocols for the walker's hardware system. Each line is labelled, and the type of each line is specified. A buck converter is used to step-up voltage for the stepper motor to increase the peak torque at a higher speed. An Arduino is used to control the linear actuators using PWM, and the stepper motor using GPIO. The jetson Nano connects to the Arduino and CAN bus using USB. The chassis motors use the CAN communication protocol; however, they can not directly communicate to the jetson, so we use a USB-CAN converter to connect the chassis motors to the jetson nano.h

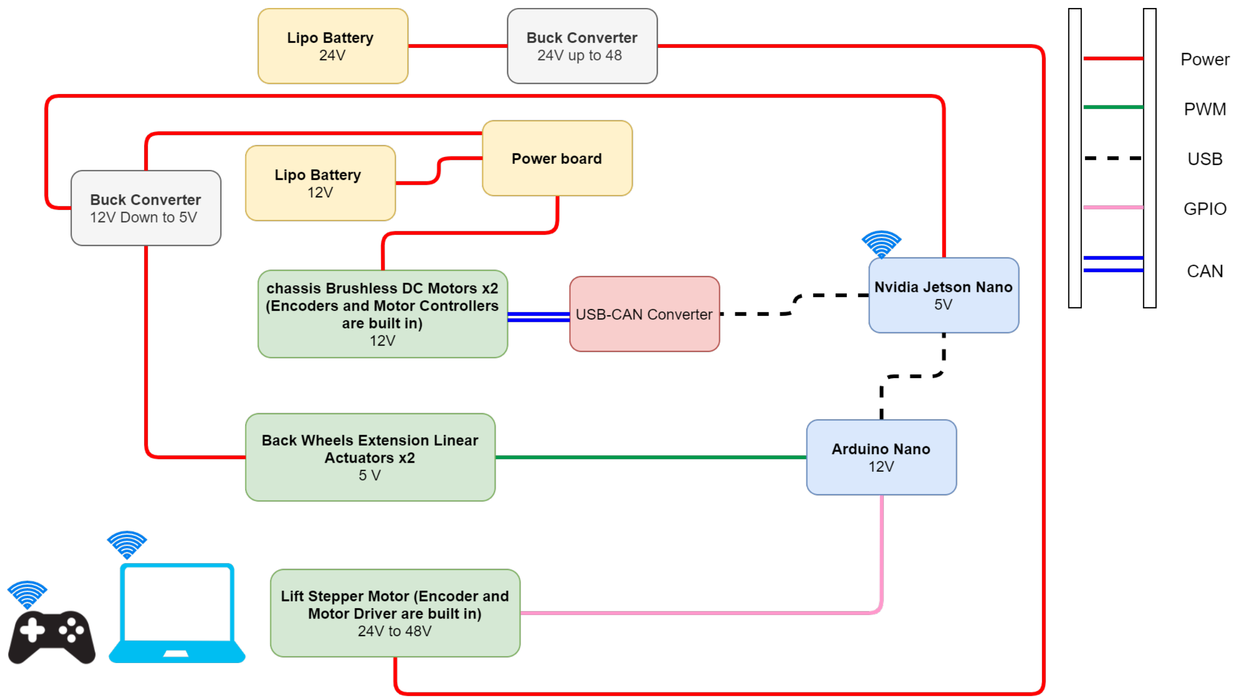
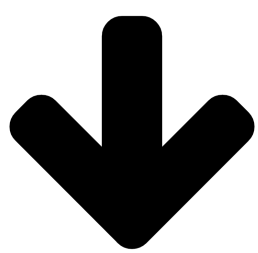


Figure 4.12: Initial Control system architecture



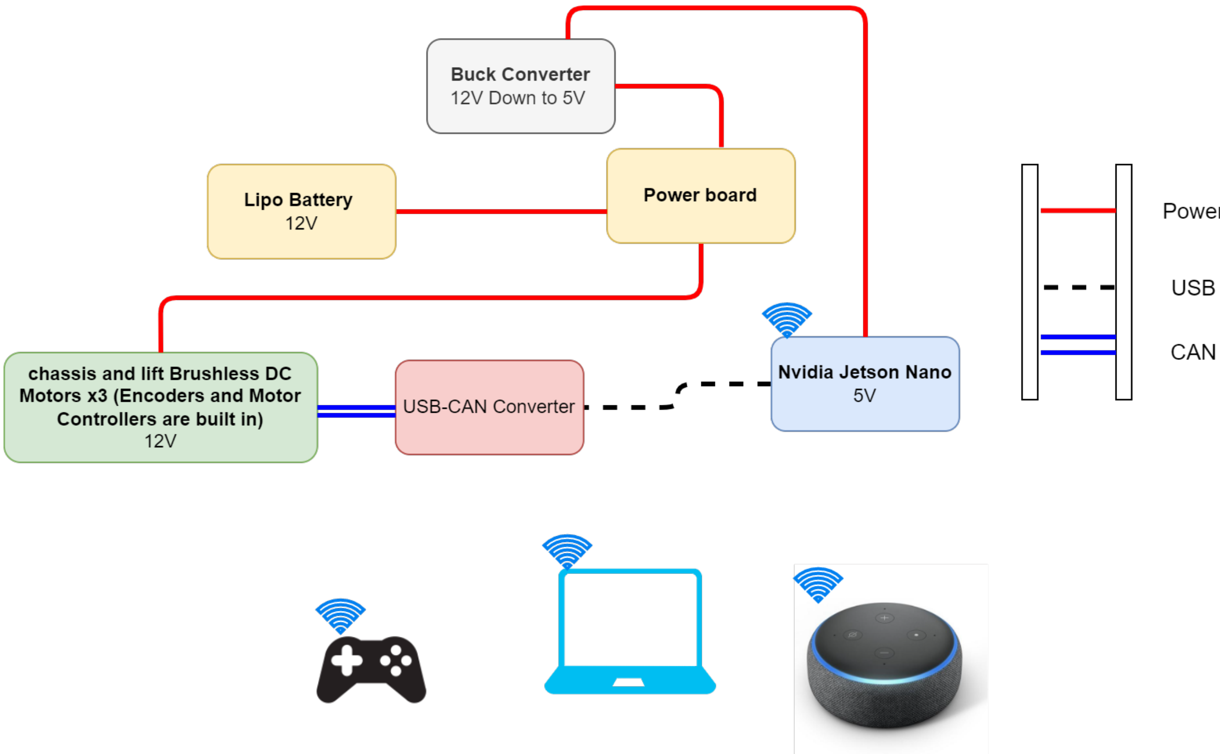


Figure 4.13: Final Control system architecture

Figure 4.13 shows the final components used in the system architecture. We removed the linear actuators and we replaced the stepper motor with a brushless DC motor similar to the chassis motors. We replaced the stepper motor to reduce weight and components used in the system, and to simplify the walker's software. We are using one 14.4 V with 8000 mAh lipo battery, we measured a current draw of 2 A using an ammeter. The battery life is 4 hours (battery capacity/load current). We added a voice control feature which allows users to communicate and control the robotic walker's actions without the need for the help of an operator. However, the walker can still be controlled using a joystick if needed. The only communication protocol is Controller Area Network (CAN). The CAN bus uses two wires for communication CAN low and CAN high, as shown in figure 4.15. Since motors use CAN communication protocol, motors can connect together in a daisy chain fashion shown in figure 4.15. As a result, we reduced the electrical components and used the most minimal cabling in the robotic walker. Also, CAN allow us to access motor encoders directly, which is not the case if PWM is used (the motor allows you to use either PWM or CAN). Moreover, the motor controller and encoder are built into the motor, saving space and better organization.

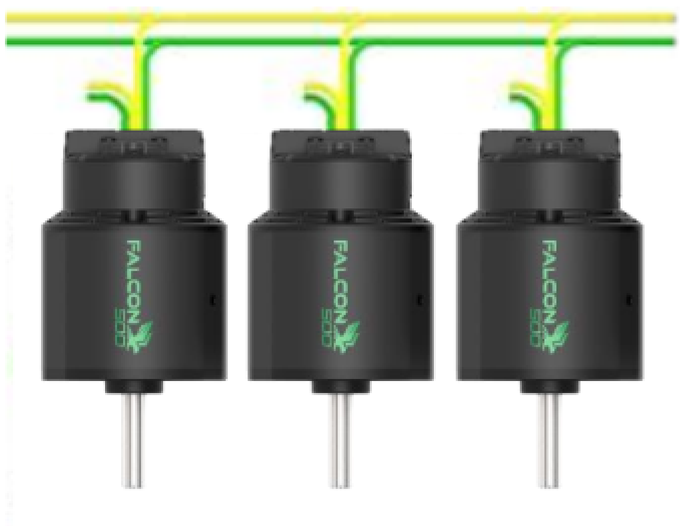


Figure 4.14: The chassis and lift motors are connected together in a daisy chair fashion

The motor chosen for the chassis and the lift is a brush-less motor, Falcon 500. A step-down gearbox ratio 10:1 to increase torque and reduce the speed at high rpm. The brushless motor is chosen based on torque, speed, and noise level. Table 4.1 is laying out the difference between brushed and brushless motors:

	Brushed motor	Brushless motor
Lifetime	Short (brushes wear out)	Long (no brushes to wear)
Speed and Acceleration	Medium	High
Efficiency	Medium	High
Electrical Noise	Noisy	Quiet
Torque	Lower	Higher

Table 4.1: Advantages our using Brushless motor in SkyWalker

The specification of the motor is shown in table 4.2:

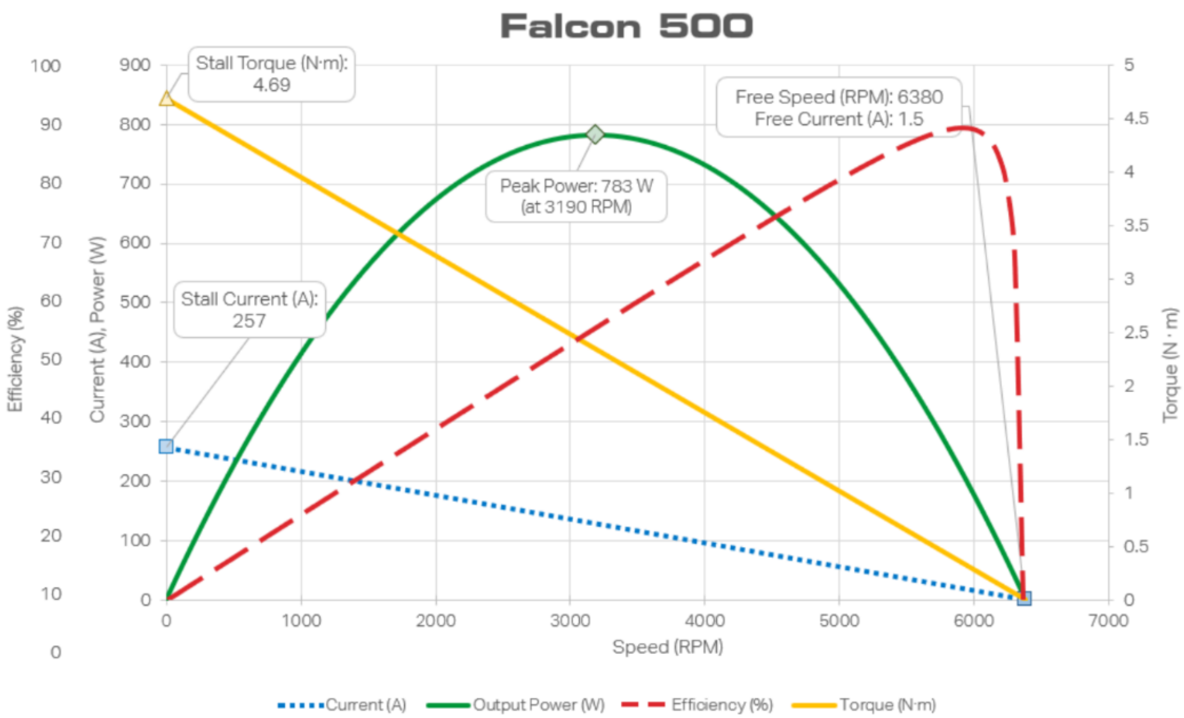


Figure 4.15: Motor specifications for speed and torque [5]

	Specifications
Motor Interface	Integrated
Communication	CAN / PWM
Direct Sensor Input	Yes, Over CAN Only
Built-In Encoder Feedback	2048 CPR Encoder
Nominal Voltage	12 VDC

Table 4.2: Motor specifications

4.5 Shell Design and walker color

A shell has been designed to cover the electrical and motor system. Key parameters considered when designing the shell are the shape and the color. For color, blue was chosen because it is the most preferred color for the elderly population of both sexes, followed by red [70]. The walker's colors are also chosen based on what older adults prefer. The handles are painted similar color to the shell and the body of the walker is cream color (RAL 9010). We designed the shell with a focus on reducing the stigma that may come with an assistive devices. According to Cheryl et al, older adults prefer assistive devices that are not stigmatized [71]. The design that is chosen is related directly to the name of the walker, as shown in figure 4.17.

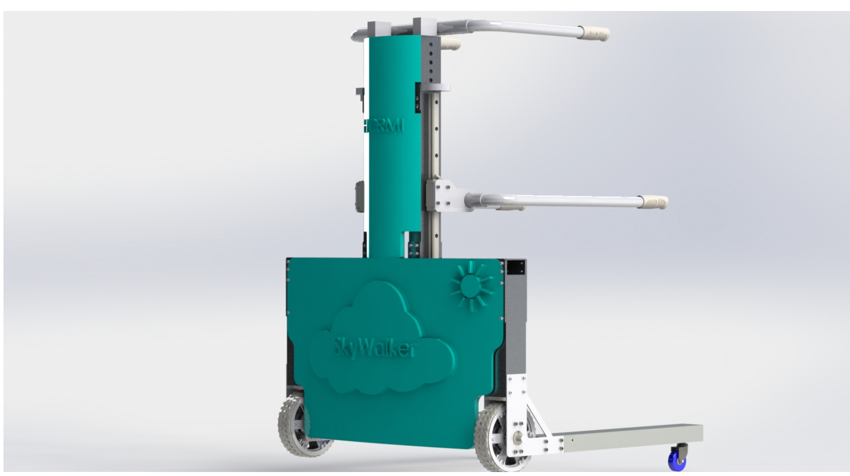


Figure 4.16: Front view of shell Design for SkyWalker to cover the motors and electronics

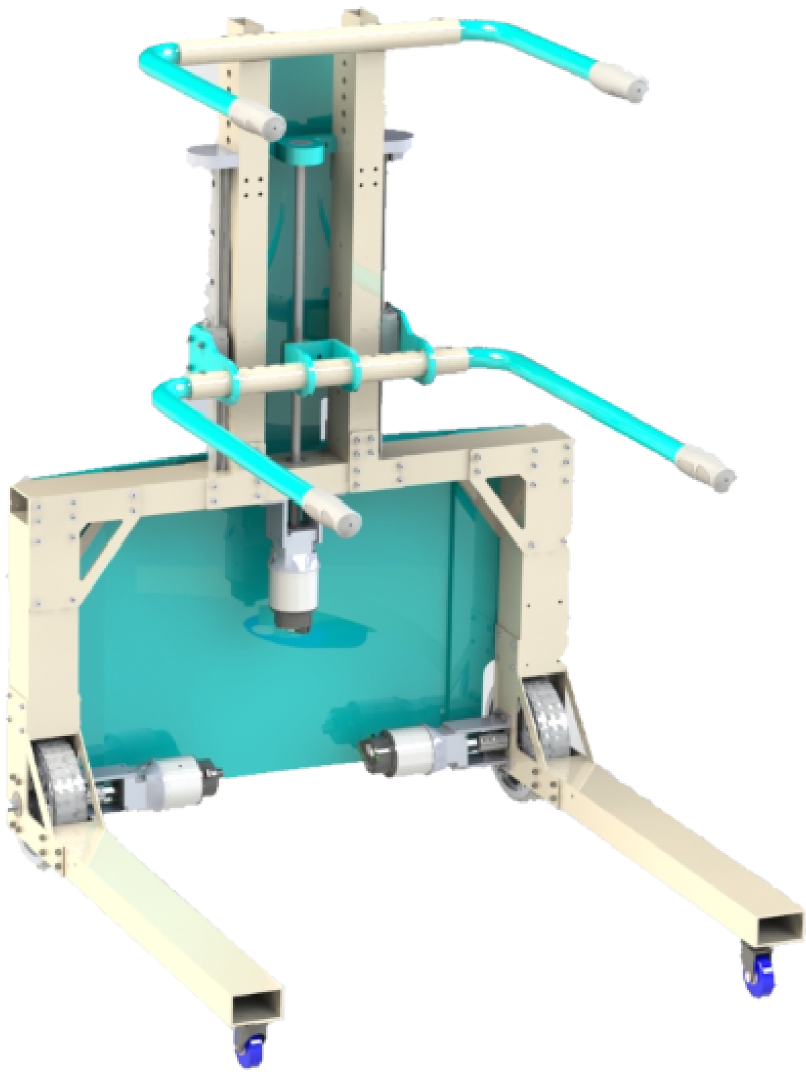


Figure 4.17: Rear view of shell Design for SkyWalker to cover the motors and electronics

Chapter 5

Software System

Safety is one of the major constraints in our system. The control system is designed to be safe and straightforward and relies on commercially available components. The system uses a lithium polymer battery with a fused power board to ensure SkyWalker does not harm the user and damage the electronics. We have also implemented safety features into the software.

In this chapter, we will discuss motor controllers we used and planning to use, trajectory generation method and voice how we implemented voice control.

5.1 Motor control

We implemented different controllers in our system. One of the controllers is PIDF controller shown in figure 5.1. The motor is controlled via velocity commands. However, before it's fed to the motor, the desired velocity of the load is scaled by the value of the feed-forward gain (F). Feedback control is added to achieve a better match between the input velocity and measured results. The diagram below shows the feedback

Position controller shown in figure 5.2 is very similar to the velocity controller we discussed above, except feed-forward is removed.

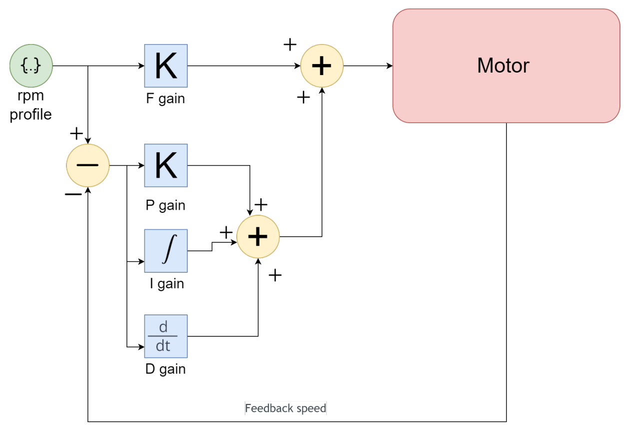


Figure 5.1: Velocity controller with Feed-forward and feedback components. The feedback portion consist of proportional, integral and derivative (PID)

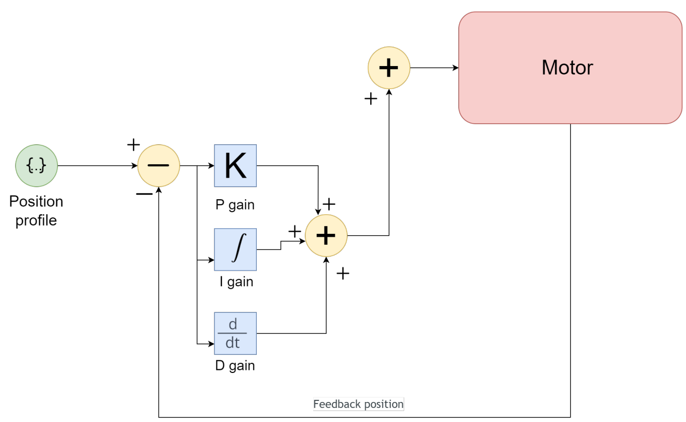


Figure 5.2: Position controller with feedback components. The feedback portion consist of proportional, integral and derivative (PID)

However, we want to have a more efficient and stable system and take away some of the burden of feedback control. This can be done by introducing feed-forward control to position control. We used the approach shown in figure 5.3 to achieve that. The inputs in the new system are velocity and position profile. The goal is to be able to anticipate the motor speed required to achieve a certain position, this requires the speed and position profiles to be coordinated which means they are not independent.

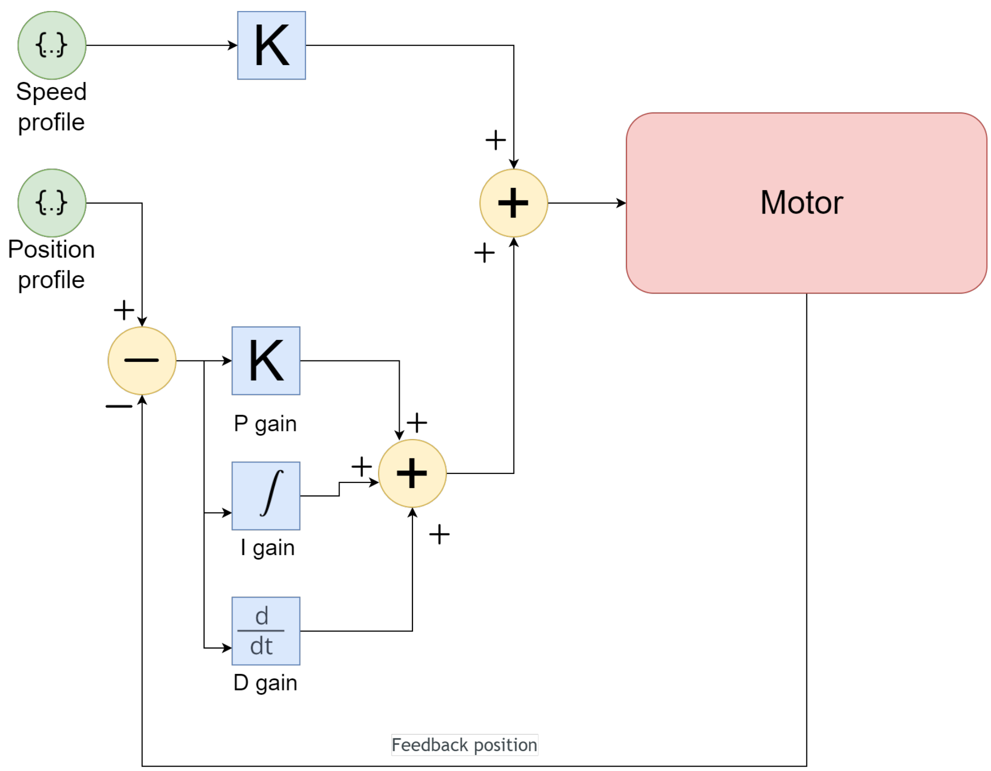


Figure 5.3: Combined velocity and position controllers. Velocity is used only as a feed-forward term while position is used for feedback

5.2 Sit-To-Stand Trajectory Generation

To generate a synchronise motion between moving forward (y direction) and lifting (z direction). I implemented both of them as a function of time. Meaning moving forward and lifting start at the same time and ends at the same time. We wanted to have a trajectory path that follows S-curve as linear curve is not recommended. To implement the S-curve shown in figure 5.4, we used a third-order polynomial function:

$$\begin{aligned} z &= ax^3 + bx^2 + cx + d \\ z' &= 3ax^2 + 2sx + c = \frac{dz}{dx} \end{aligned} \tag{5.1}$$

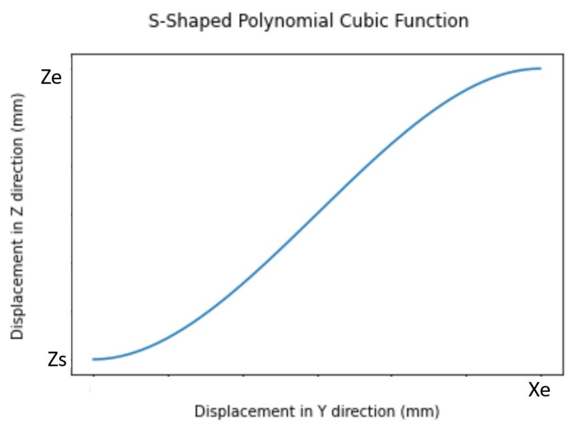


Figure 5.4: Concept sketch of the planned S-curve trajectory of the walker, showing the path along the horizontal and vertical axes

We know the end point of the trajectory x_e and z_e, and we know our starting point for the trajectory z_s as well.

$$\begin{aligned} z(0) &= d = z_s \\ z'(0) &= c = 0 \end{aligned} \tag{5.2}$$

Then we solve for the constants a and b in the polynomial function:

$$
\begin{aligned}
z\left(x_e\right) &= a x_e^3 + b x_e^2 + z_s = z_e \\
z'\left(x_e\right) &= 3 a x_e^2 + 2 b x_e = 0 \\
xe \neq 0 &\Rightarrow 3 a x_e + 2b = 0 \\
b = -\frac{3 a x_e}{2}
\end{aligned}
\tag{5.3}
$$

We take the b we found in 5.3 and we apply it to 5.4:

$$
z\left(x_e\right) = a x_e^3 + b x_e^2 + z_s = z_e
\tag{5.4}
$$

$$
\begin{aligned}
a &= \frac{2\left(z_s - z_e\right)}{x_e^3} \\
b &= \frac{-3 a x_e}{2} \\
&= \frac{-3\left(\frac{2(z_s - z_e)}{x_e^3}\right) x_e}{2} \\
&= \frac{-3\left(z_s - z_e\right)}{x_e^2}
\end{aligned}
\tag{5.5}
$$

Then we substitute the a and b we found in 5.5 to 5.1.

We used python to generate S-shaped curve, which then took the derivative of the curve and fed the velocity to our velocity motor controller.

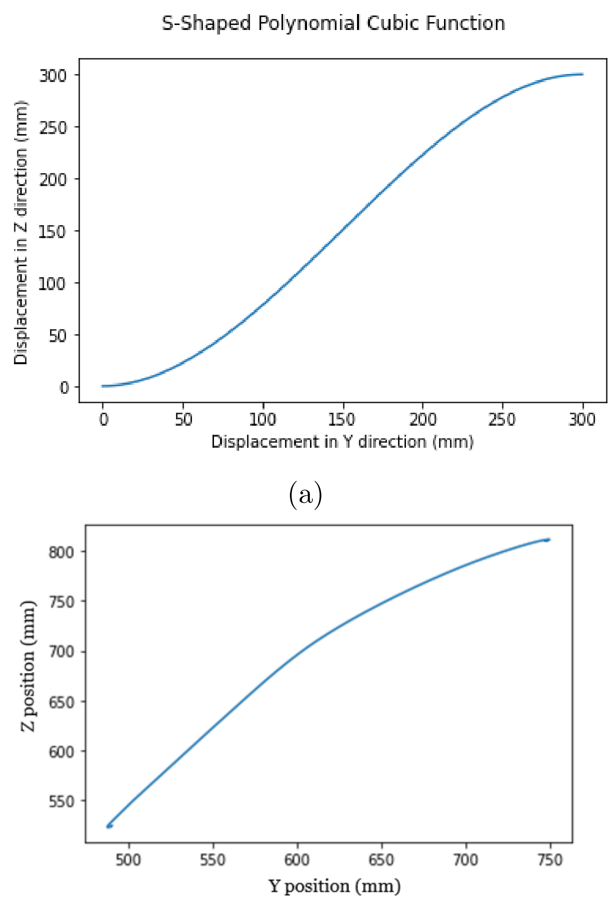
Couple of things we have to input:

1. The start point
2. The end point
3. The total time
4. The velocity curve of $\dot{x}(t)$.

We chose a smooth velocity curve to $\dot{x}(t)$: an S-curve velocity profile was used to ensure smooth motion by minimizing jerk and reducing oscillation of the mechanism, resulting in a more controlled and reproducible trajectory. This velocity curve is is used to calculate $\dot{z}(t)$.

$$\dot{z}(t) = z'(x) \cdot \dot{x}(t) \tag{5.6}$$

However, the velocity controller we implemented resulted in a linear path instead of S shaped path shown in figure 5.5. The controller was not following the desired path which is the result of tuning issues in the PID parameters. The controller was not tuned properly and currently working on tuning the controller.



(a)

(b)

Figure 5.5: The desired path in 5.5a vs the actual path in 5.5b

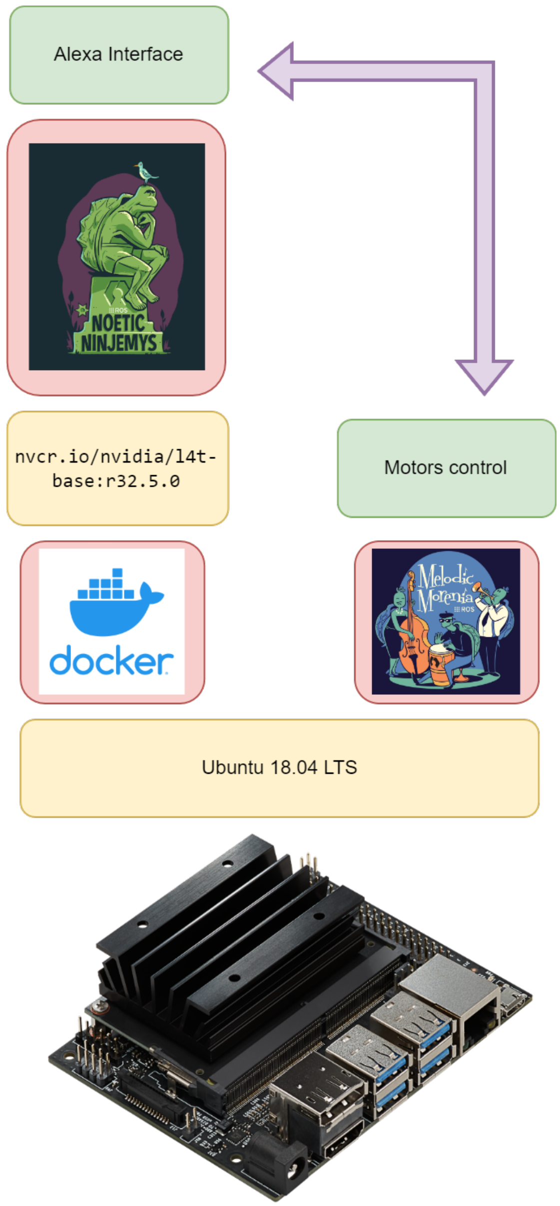


Figure 5.6: Software design for the walker implemented on the Jetson nano compute unit shown in the image. The Jetson runs Ubuntu 18.04 and ROS melodic where the motor controller program resides. In order to interface with amazon web services, a docker image with a custom lightweight operating system running ROS noetic is used. Alexa commands are communicated from a script running on ROS noetic to the motor controller program running on ROS melodic using TCP communication.

5.3 Voice Control

One of our primary design requirements is "**The design must be easy to use**" which made us think about how we can build an experience that offers users a more intuitive way to interact with the robotic walker they use on a daily basis. Moreover, the feature we are adding should not increase the complexity of the hardware system on the device. These conditions lead us to choose voice control as our method to give users the ability to control the actions of the device without the need for external assistance. We are using a cloud-based voice service Alexa, which allows us to control SkyWalker. There are three ways to integrate Alexa functionalities into your device shown in table 5.1.

Pub-Sub	Bluetooth	Direct
When a device has internet connection	Communication with a device over Bluetooth	Direct communication with the device via microphone
No distance limitation	No mic, speakers, audio-processing required	The functionality of an Amazon Echo built into any device

Table 5.1: Methods developers can integrate Alexa into their devices

We are using Alexa Echo Dot (3rd gen) device shown in figure 5.7 [1]. The device consists of a speaker and 4 microphones which allows an interaction between the robot and the user. Moreover, the size of the device is relatively small, which allows it to be added to the walker. Currently, we implemented the Pub-Sub method where Alexa and SkyWalker communicate over the internet. Connecting over the internet gives a considerable advantage in terms of features we can implement in the future, like giving commands to the walker to come to the user from different rooms. In the future, we will connect Alexa Echo Dot and the robot through Bluetooth for offline environments.

In order to use Alexa intereface in our robot we need to use Alexa Skill Kit (ASK) which is provided by Amazon. Alexa Skill Kit (ASK) allows robot developers to build a natural voice interface for their robots. Alexa receives the user's voice command through an Alexa enabled device like Amazon Echo Dot Gen 3 and converts the command to a text message. This text message is published to a IoT topic in Amazon Web Service (AWS) which then the robot receives the text commands by subscribing to AWS IoT topic and excutes the commands. The details of the interaction process between the user and the robot is shown in figure 5.8 To building an Alexa-controlled robot, you need to do the following main steps [2]:

[1] https://moderncastle.com/smart-home/amazon-echo-dot-3rd-generation-review/
[2] https://aws.amazon.com/blogs/robotics/build-alexa-controlled-robot/

Figure 5.7: Echo Dot (3rd gen) dimensions and components

1. Create an IoT thing account in AWS IoT.
2. Create an Alexa skill.
3. Write the code for IoT MQTT Client and intent handler
4. configure AWS in our controller
5. Install ROS on your robot controller and write a listener file to receive the text messages

For example, in case one of the desired commands is to to turn right, we need to create an intent (a command) that will be sent to the robot controller. This intent (command) gets triggered when Alexa hears one of a few possible sample Utterances. An utterance is something the user might say to invoke desired intent. In Figure 5.9, I created an intent called "right". This intent is invoked when the user says any of the following Utterances (phrases) shown in figure 5.9 after saying the activation phrase. I can add as many Utterances as needed. Once the intent is triggered, a message will be sent to the SkyWalker controller, executing the turning action. An important note to consider, Alexa will not execute the command if the user does not say an activation phrase before saying the Utterances. It is similar to when someone wants to use Siri on iPhone; they say the activation phrase "Hey Siri" so it listens to what the user wants to ask, "how is the weather today ?" as an example. In SkyWalker, the user says "activate robot", then says one of the utterances for turning right, "go right" and then the command will be executed. The developer can choose the activation phrase.

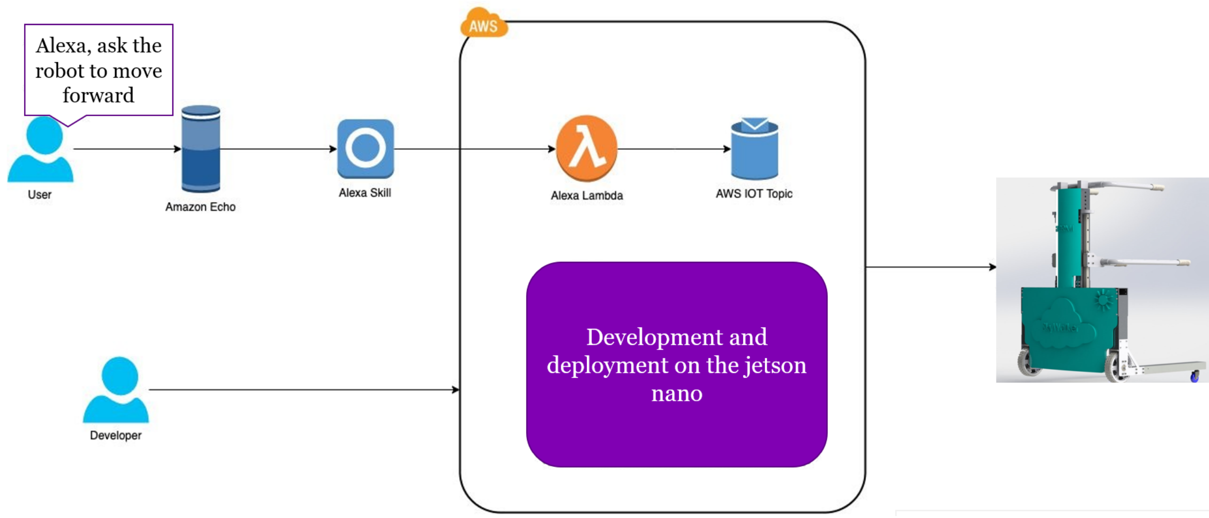


Figure 5.8: The user can give a command to any amazon device, and through ASK and AWS, the voice message is converted into a text and sent to the SkyWalker controller. Once the text message is received in the controller, the desired command will be executed.

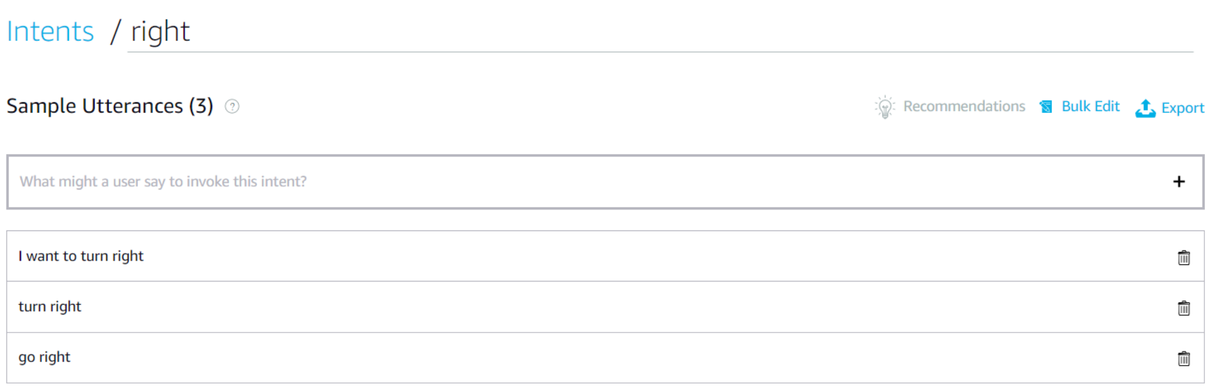


Figure 5.9: Screenshot of the amazon web services portal. This shows what a user can say to invoke the intent "right"

Chapter 6

Experimental Validation

This chapter discusses the STS and walking experiments conducted to test skywalker functionalities. The STS experiments have been conducted in the motion capture lab. Subjects were asked to fill out a questionnaire after every different trajectory they did. An interaction study has been conducted for walking with SkyWalker. The study was conducted in multiple locations, in indoor and outdoor areas. Finally, an interaction study was conducted for voice control features.

6.1 Biomechanical studies of sit to stand motions

Controlling the walker during STS motions is more challenging than for walking motions, and the choice of handle trajectories resulting from coordinated upward and forward motions for the device is less straightforward. Some preliminary biomechanical studies on STS motions assisted by the SkyWalker have been performed in the motion capture lab to get insights.

6.1.1 Participants

Healthy participants have been recruited for the experiment (1M, 1F), with an average height of 168$\pm$2 cm and an average weight of 57$\pm$5 kg. All participants had no previous record of injury limiting their ability to perform the STS. The experiment has been approved by the ethics committee at the University of Waterloo.

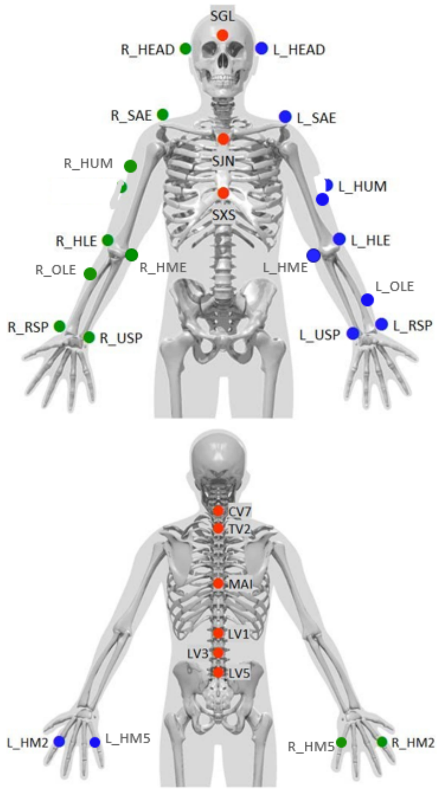


Figure 6.1: IOR markers upper body

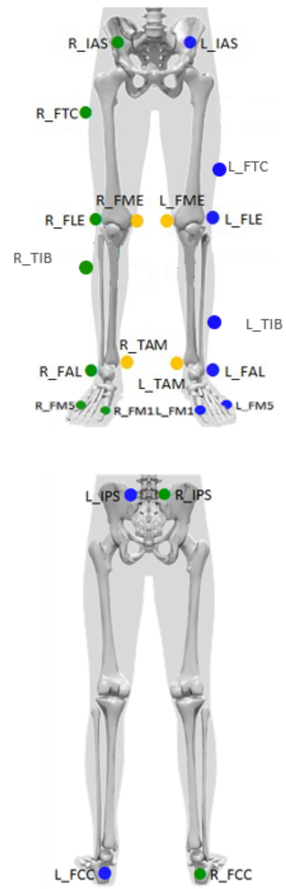


Figure 6.2: IOR markers lower body

6.1.2 Procedure

STS movements of the subjects were recorded with Vicon motion capture and analysis system. The recorded data is sampled at 100 Hz. Reflective markers were attached to the participant's body following a modified version of the IOR marker set shown in figures 6.1 [72]. The data from the motion system has been filtered using Savitzky–Golay filter with a window length of 5 and a degree 3 polynomial. Two Bertec force plates (FP) were used to record forces and centers of pressure. The subjects were seated on a chair, standing on one FP, and the feet were placed on the other FP. FP was used to collect center of pressure (CoP), force (F), and moment (M) data on three axes each. The force plates data was recorded at 1000 Hz.

	Forward travel distance (cm)	Trajectory periods (seconds)
Trial 2	20	3, 5
Trial 3	30	3, 5
Trial 4	40	3, 5

Table 6.1: 6 different trajectories with different forward travel distances and different trajectory durations

The subjects were asked to perform six different trajectories using the robotic walker, and each trajectory was repeated three times. The trajectories involve different forward travel distances and different trajectory duration shown in table 6.1. The lower handles vertical travel distance is fixed to 30 cm in all trajectories.

The subjects selected the position of the feet before initiating STS action. The STS movement starts lifting the user by simultaneously providing vertical support using the vertical lift and forward motion by moving the chassis for a specific distance. The operator initiates the STS motion after confirming with the subjects that they are ready to stand up. The subjects did not have any training with the device before the experiment.

Modified NASA Task Load Index survey (RTLX) was used to record the subject's feedback. The subjects were asked to fill out the survey for each trajectory after repeating each trajectory three times. The subject completed 6 RTLX questionnaires, one for each trajectory. RTLX is a tool to evaluate tasks by measuring mental demand, physical demand, temporal demand, performance, effort, and frustration. However, in this study, the workload is not calculated and only the score given for each demand is evaluated except for mental demand and performance.

Physical demand: How physically demanding was the task ?

Temporal demand: How hurried or rushed was the pace of the task ?

Frustration: How insecure, discouraged, irritated,stressed and annoyed were you ?

Effort: How hard did you have to work to accomplish your level of performance ?

6.1.3 Results

Modified RTLX and Survey

Based on participants' score for each task, a walker trajectory that is 3 seconds long have a higher mental and temporal demand load across different forward travel distances, with the subjects exerting more effort to stand up, uncomfortable, and unsafe while using the device.

The 5 seconds trajectory period shows the lowest scores for different demands between the trajectories. It shows that trajectories with 5 seconds period are physically less demanding, and subjects did not have to work hard to accomplish the task compared to other trajectory periods. Moreover, subjects experienced lower temporal demands.

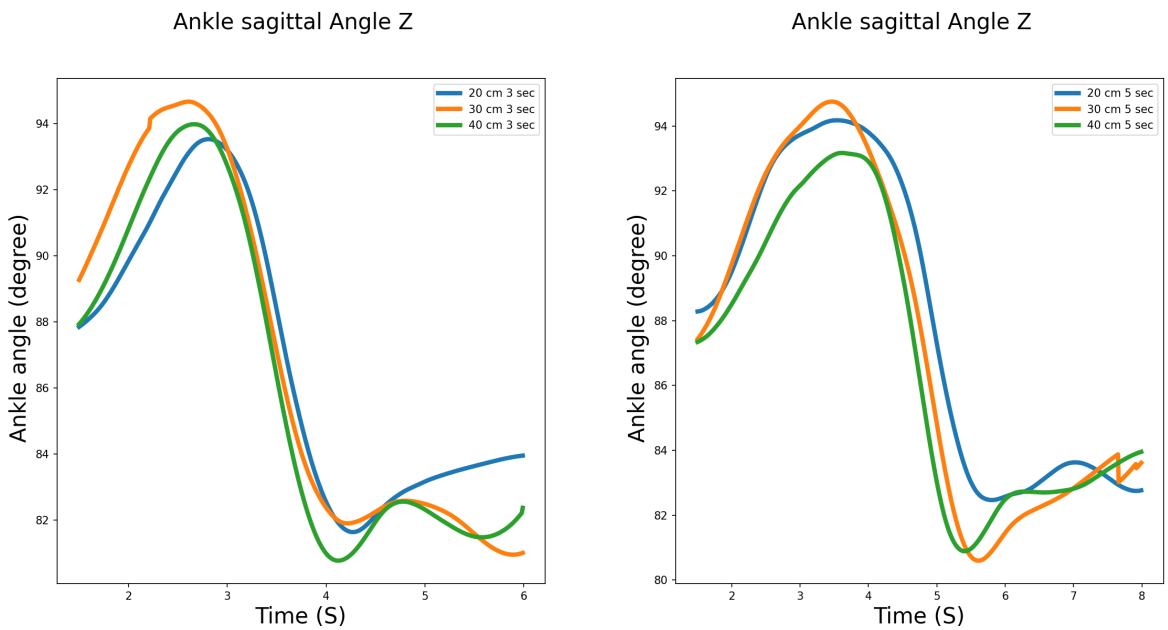
At the end of the experiment, a custom survey was given to the subjects. They indicated that 5 seconds period was preferable because it created less effort to stand up and was less rushed compared to the others. Three seconds period was the least preferable trajectory period because they felt rushed. Trajectories with 20 cm forward travel distance were short because their knee did not fully extend when the walker stopped moving, and they felt more load on their upper body. The 30 cm travel distance was the most preferred since their knee was able to be fully extended and had the least physical demand on the upper body. However, a forward travel distance of 40 cm felt that the walker went forward too much and had to take a step forward to adjust their position. Finally, the subjects in the survey indicated that the transition from the lower handle to the upper handle once the walker fully stops is easy and comfortable.

Travel distance (cm)	time (s)	Physical demand	Temporal demand	Frustration	Effort
20	3	6	11	4	4
	5	4.5	7	10.5	9
30	3	4	11	1	4
	5	3	6.5	1	3
40	3	4.5	11	2	4
	5	5	7.5	1.5	4

Table 6.2: Modified RTLX survey results

Kinematics and Kinetics

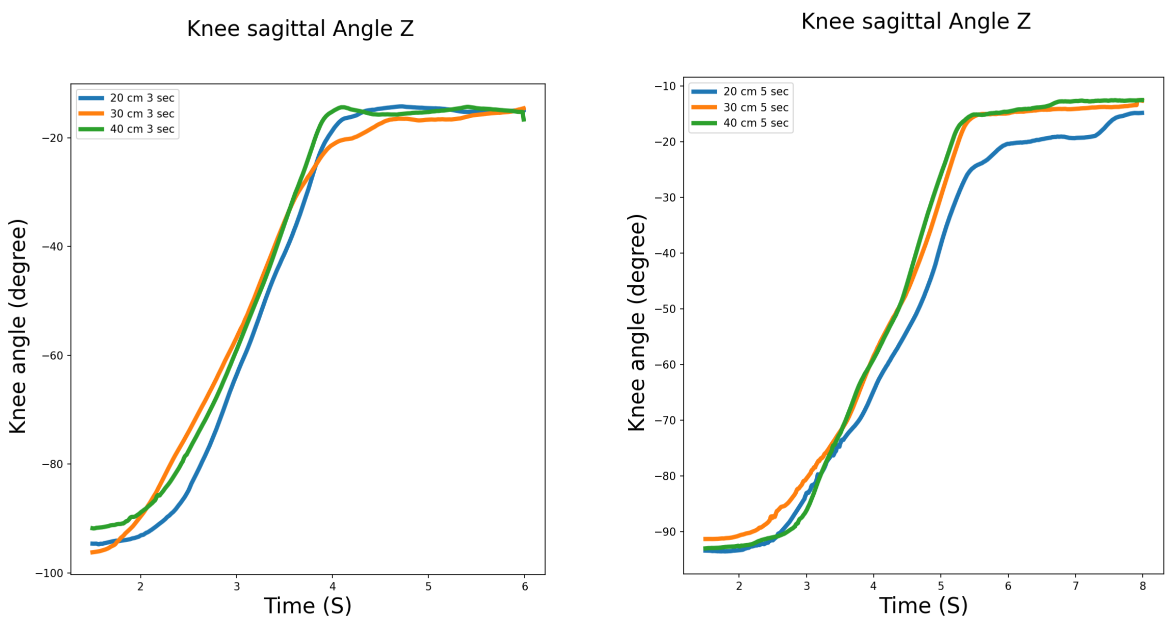
The averages of the shank, thigh, trunk, and foot angles have been plotted for all six trajectories. The plots show the transition between the sitting and lifting phases shown in 3.5. For example, looking at the knee angle for 5 seconds walker trajectory period, the sitting phase starts from the beginning and ends at 1.5 seconds. The lifting phase starts from 1.5 seconds; a significant change in the angle starts from around -95 to -15 degrees, ending around 6.5 seconds. Similar observation to the example above can be seen at the other joint angles, including the hip and ankle, and for different trajectory periods.



(a) (b)

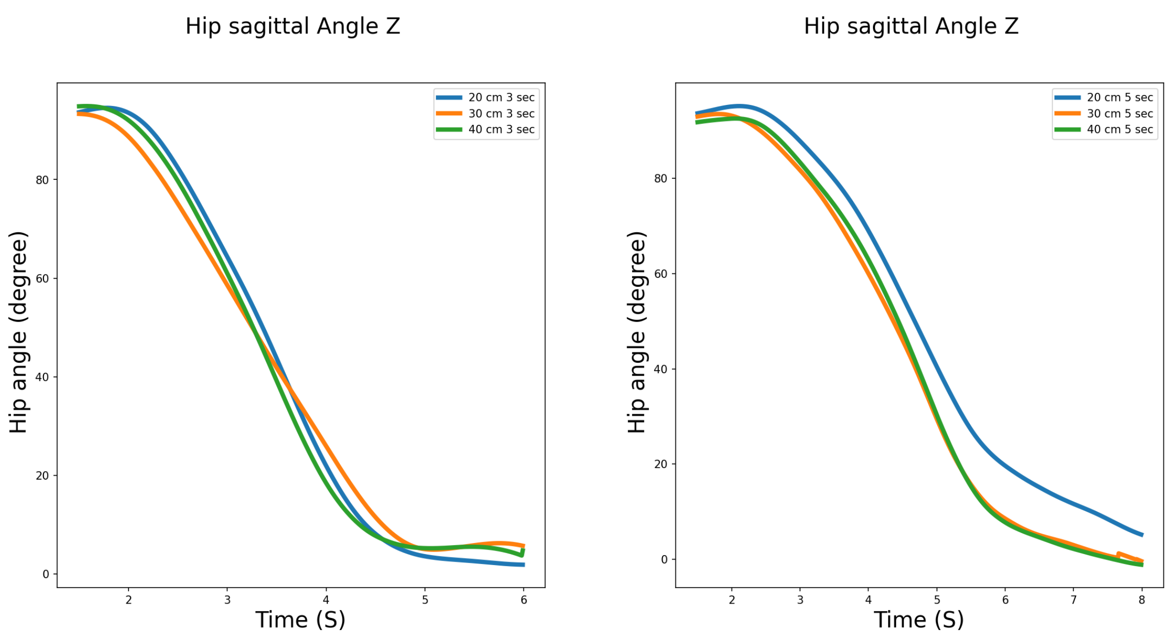
Figure 6.3: Kinematic of STS for a subject for trajectories. Joint shown is Ankle dorsi flexion

However, it is hard to observe the transition from the lifting phase to the switching phase for most of the trajectories except for the upper trunk angle. Looking at the upper trunk angle for 3 seconds walker trajectory period, the change between the 3 phases can be seen where the switching phase is observed when the subject rises from the lower level to the upper level after 4.5 seconds. The maximum vertical ground reaction force (GRF) coincides with peak hip flexion and max knee extension. The vertical GRF coincides with the inclination of the trunk and ankle dorsiflexion in terms of time to switch phases. Looking at 6.7, a clear distinction between the 3 phases presented in this paper can be seen for trajectories with 5 seconds period but hard to observe for trajectories with 3 seconds period.



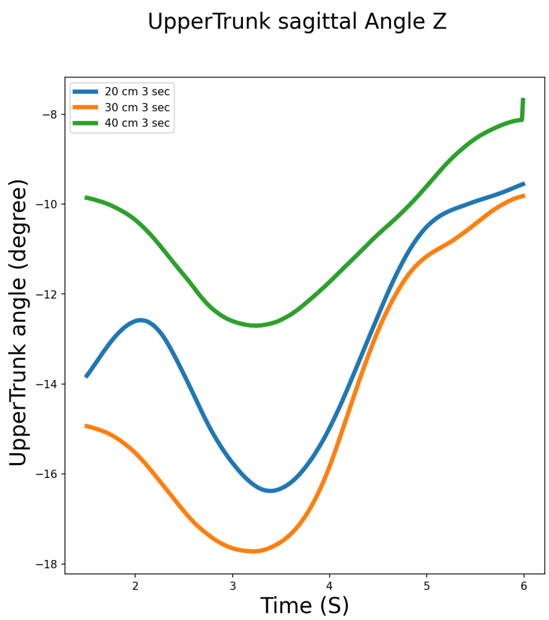
(a) (b)

Figure 6.4: Kinematic of STS for a subject for trajectories. Joint shown is Knee flexion



(a) (b)

Figure 6.5: Kinematic of STS for a subject for trajectories. Joint shown is hip flexion



(a) (b)

Figure 6.6: Kinematic of STS for a subject for trajectories. Joint shown is Trunk flexion/extension

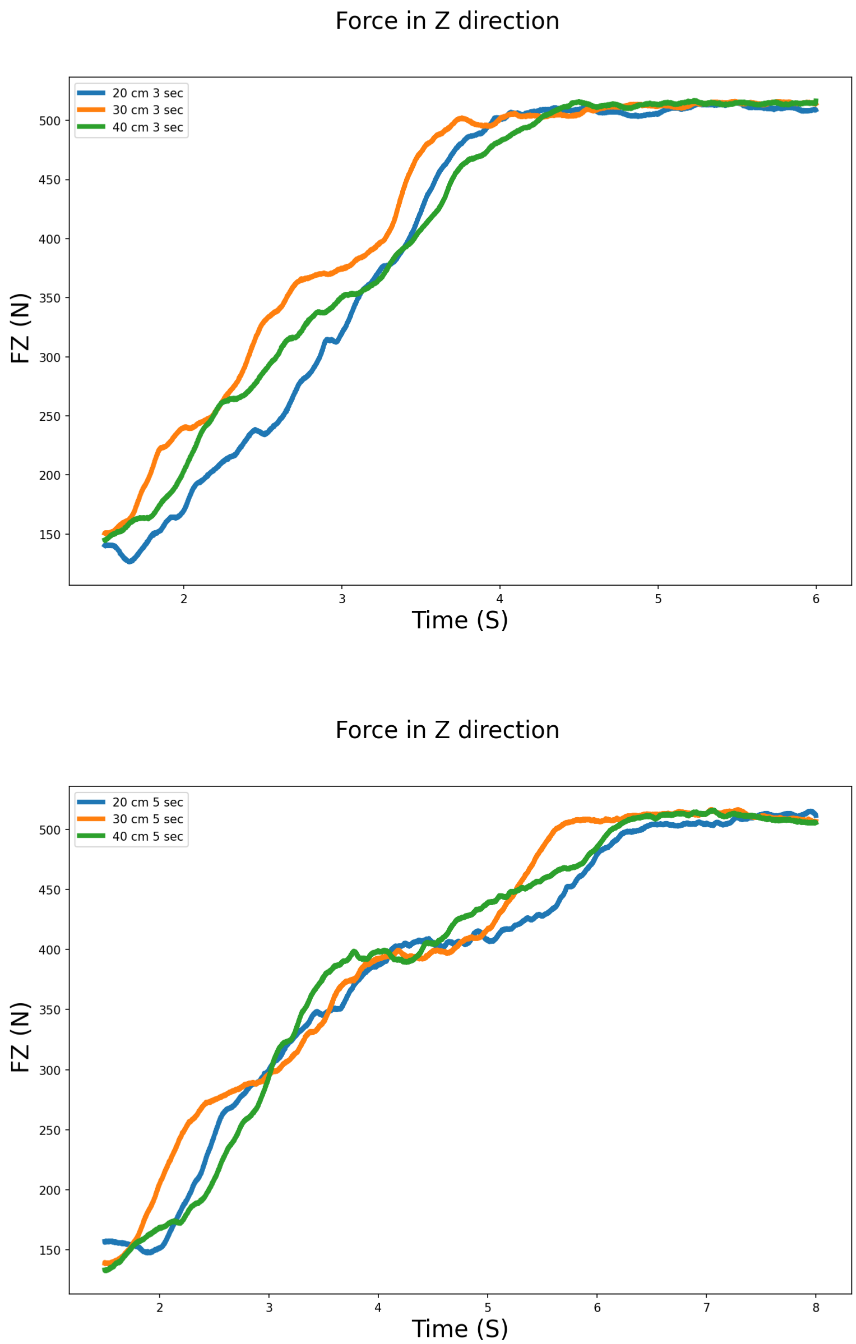
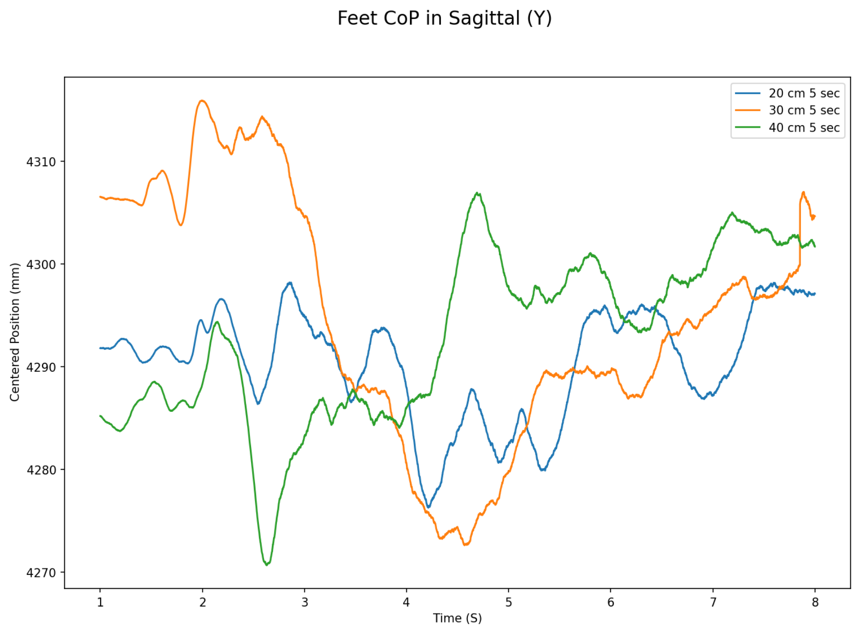


Figure 6.7: Vertical ground reaction force for a subject for all trajectories



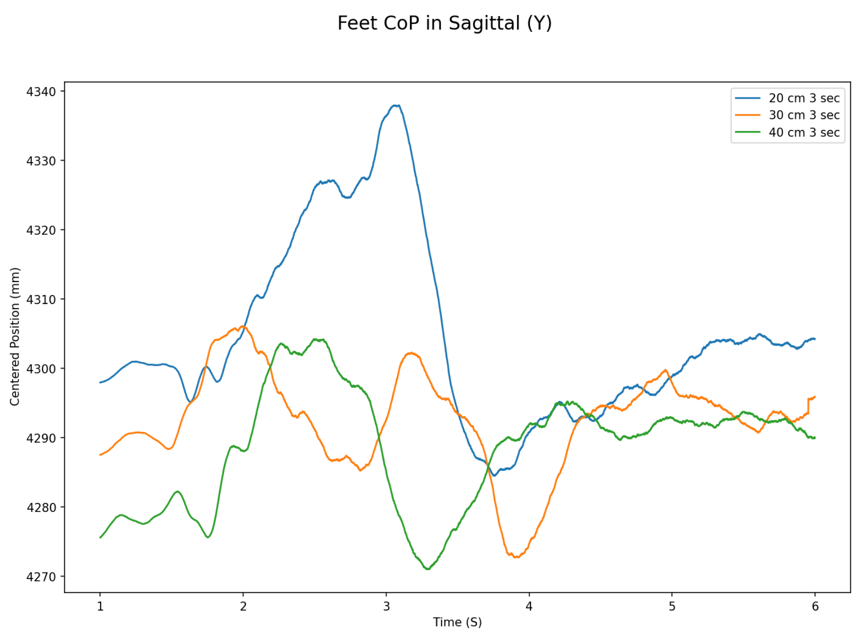


Figure 6.8: Feet CoP in Saggittal (Y) force for a subject for all trajectories

6.1.4 Discussion

A study was performed to examine the feasibility of the device by observing the kinetics and kinematics of the subjects and their feedback on each trajectory using the RTLX questionnaire and survey. Based on the RTLX questionnaire and survey, the subjects' most preferred trajectory is a 30 cm forward travel distance over 5 seconds. The preferred forward distance is directly related to their height [73] since the length of the lower leg is proportional to the horizontal travel distance needed to perform STS. Despite the fact that most of the load is taken by the user's arm, the extended duration where the knee is not fully extended resulted in fatigue in the knee joint. Moreover, with a 20 cm forward travel distance, the user experienced a significant load on the shoulder joint because they felt that most of the support provided to stand up was happening in the vertical direction and a large load on the knee joint since it was not fully extended. The frustration score in the RTLX questionnaire was the highest for trajectories with 20 cm compared to the other distances feeling insecure during STS motion. For 40 cm distance, the subjects indicated that they felt the need to take a step forward while shifting their body weight during the trajectory. The frustration score in the RTLX questionnaire was lower than trajectory with a 20 cm forward distance but higher than 30 cm.

For different trajectory periods, having a longer trajectory will result in the lower limbs needing to produce a large force to support the upper limbs since it will take a long time to switch from trunk flexion to trunk extension[74]. Having said that, Li et al [73] suggest that assistive devices should have a trajectory period between 1.6 to 5 seconds. During this study, both subjects felt that 3 seconds trajectory period was rushed, which caused them to feel insecure while performing STS. For 5 seconds trajectory period, the users felt safe and were not too fast or slow. However, they indicated that trajectory periods should not be longer than 5 seconds.

By examining figures above, we can see the trajectories are similar to a typical STS movement without assistance and thus do not adversely impact the movement. Sample trajectory without assistance can be seen in [2]. Given the aforementioned comparison and user feedback, SkyWalker shows great potential as a safe assistive device for STS task. Please note that more subjects are needed, and comparisons of non-assistance trajectories need to be recorded to evaluate the walker further.

6.2 Walking trial

Two participants (2 females) with an average age of 23 years old. with a were asked to drive the walker in an outdoor and in an indoor environment. During the walking trial, SkyWalker was teleoperated using a joystick-controlled. The participants were asked to follow the SkyWakler movement. For indoor walking, subjects walked around obstacles to test the performance of SkyWalker as shown in 6.10. Figure 6.13 shows some of the paths the subjects took while walking. Figure 6.12 shows the SkyWalker going out of the elevator. The subjects were able to get into the elevator and turn 180 degrees in the elevator. The dimensions of SkyWalker are chosen based on the commercial sizes of rollators. We looked into the average indoor and outdoor dimensions, meaning the device can go through most doors easily. The speed of SkyWalker is adjusted to be around 0.95 m/s during walking so its similar to the speed of an older adult. However, the speed was adjusted based on the subject's preference. There was no collision incident during the walking trial. Figure 6.12 shows SkyWalker assisting a subject walking in an outdoor environment on different terrains. The width and the height of the upper-level handles of SkyWalker were adjusted according to the subject's preference. One issue that can be fixed is that the SkyWalker is noisy when walking on even terrain. This is because of the caster wheel on the back, which will be replaced in the future.

For turning, we utilize different methods such as on-spot turning (turning with two wheels) and on wheel moving while the other is stationary shown in figure 6.11. The participants preferred on-wheel turn as it was smoother, and they had to do less movement than an on-spot turn. However, the on-spot turn was better in tight areas for turning, like in elevators. The common theme was that SkyWalker is easy to navigate and walk around obstacles in indoor and outdoor environments.

Figure 6.9: Subject is walking into the elevator using SkyWalker, turning around and going out of the elevator

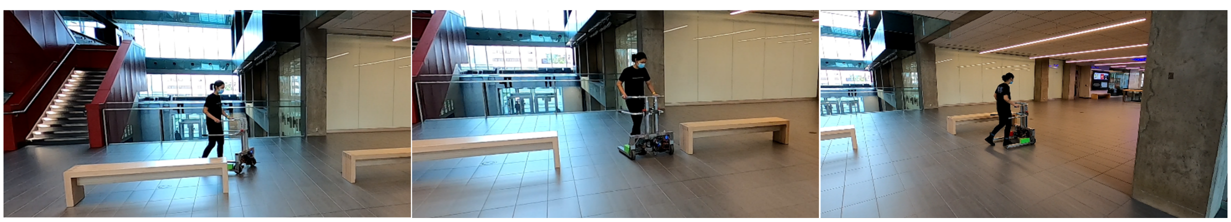


Figure 6.10: Navigation around indoors obstacles with the SkyWalkers

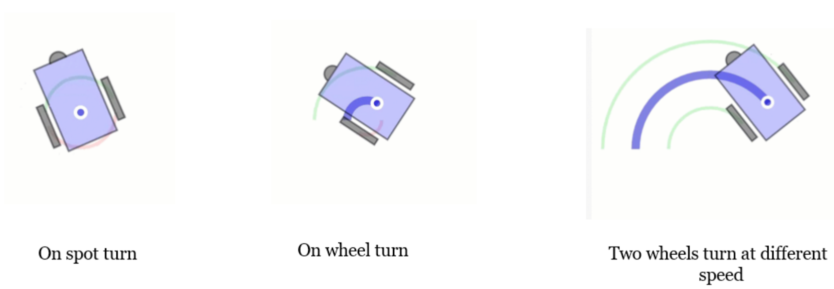


Figure 6.11: Three different types of turning. On spot turn will not change the robot position, only direction. Two wheels at the same speed need to go in opposite direction to stay in place. On wheel turn happen when one wheel is stationary and the other wheel rotate. This will change the position and the direction of the robot. It has a bigger turning radius compare to the on spot turn. Finally Two wheels turn at different speed has the biggest turning radius between turning types. it happen when one wheel is turning faster than the other on

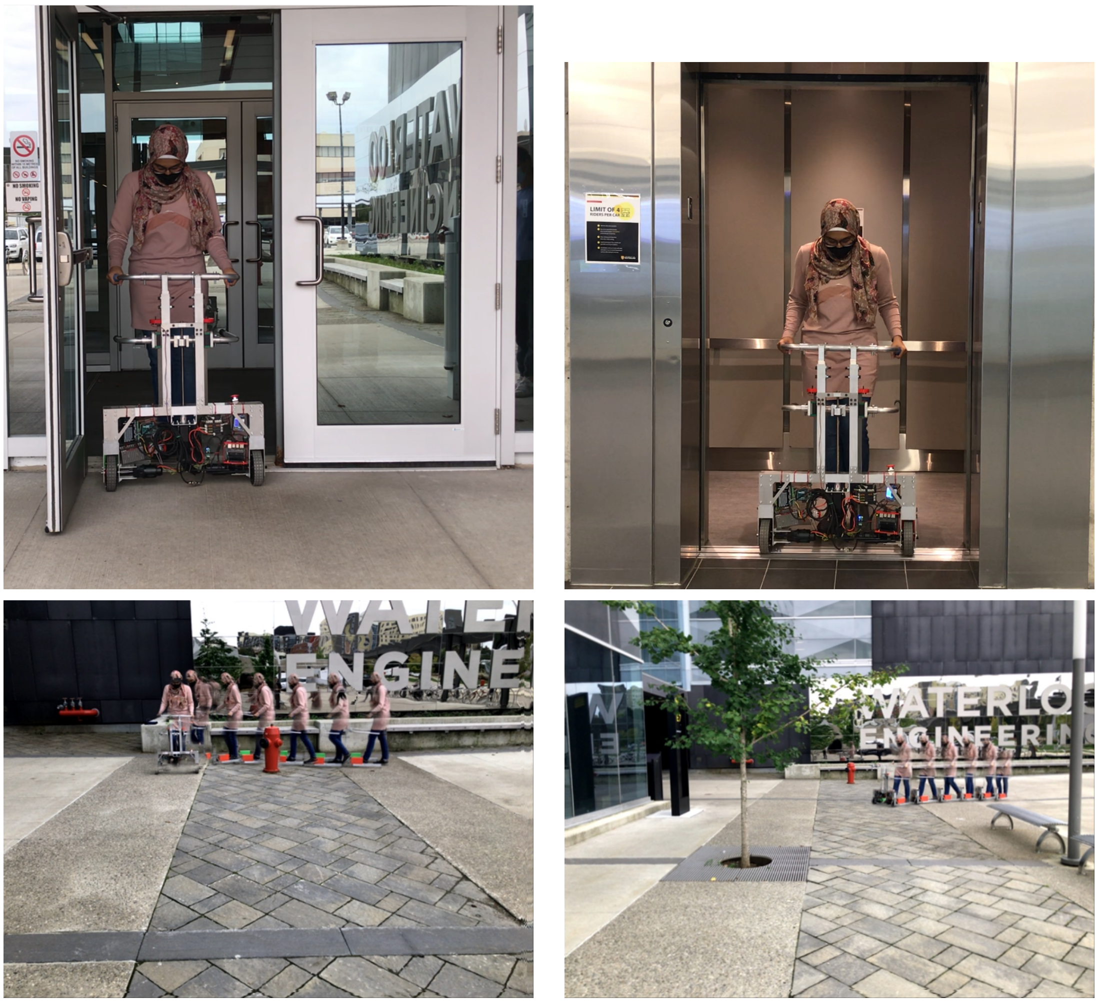


Figure 6.12: Evaluation of SkyWalker in different challenging indoor and outdoor environments (passing entrance and elevator doors, walking on different (rough) outdoor terrains, moving around outdoors obstacles). Note that the figures show the old electrical system.

Figure 6.13: Path taken by the walker during walking trials

6.3 STS using voice control interaction study

At the beginning of the study, the subjects are asked to choose any activation words (only 2 words, Alexa doesn't accept one word). The subjects are asked to choose activation words that are easy to say for them. The subjects were informed about the the phrases they can say to stand up.

The subjects selected the position of the feet before initiating STS action, the width of the handles and the height of the upper handle are chosen based on the subjects preference.The subjects activate the voice control by saying the activation word. SkyWalker let the subjects know it hard them by saying:

"Welcome, what would you like SkyWalker to do?"

Then the subjects say one the phrases to initiate stand-up command shown in figure 6.14. Once the subjects says one of the phrases, the walker start STS action. The subjects preferred the voice control method because because they can control when to start he action instead of an operator assisting them. However, they indicated that a warning or confirmation that Alexa heard them before starting the movement would make them feel safer. The feedback from subjects was positive; they thought it was easy to interact with SkyWalker since they don't have to do anything while preparing to stand up other than using voice commands. Walking using voice control was not tested, however experiments controlling SkyWalker speed and direction will happen in the future.

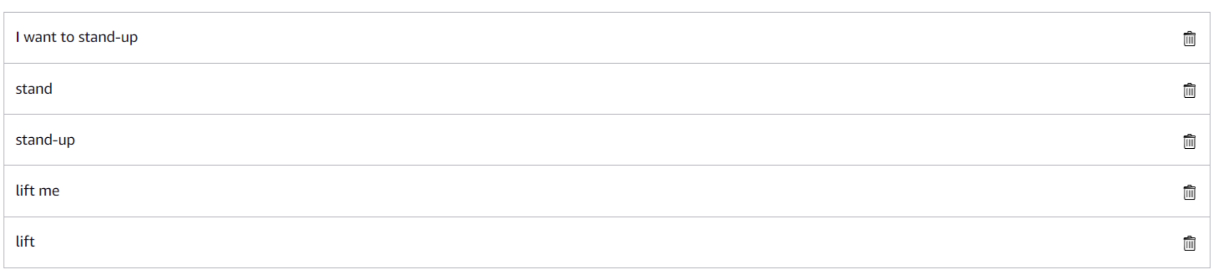


Figure 6.14: Key words or phrases to initiate STS action

Chapter 7

Conclusion and Future Work

7.1 Summary of Contributions

In this thesis, a novel robotic walker was presented. SkyWalker was designed based on the following need statement:

A need exists to assist older adult with mobility impairment, specifically with poor STS performance, to stand up, sit down and walk safely

My work on this project includes the design and the fabrication of the mechanical system, the design of the hardware system and the design and setup of the software system. Moreover, I was responsible for conducting experiments and analyzing the results. The mechanical design is made of rectangular and circular Aluminum tubes cut to the correct length. The gussets are custom designed for the robot. All of the electronics are from off-the-shelf components. The software uses ROS and c++, and python languages to operate the robot.

SkyWalker is able assist users to have the ability to stand-up from a sitting position in different environments and have the ability and encourage walking in an indoor and outdoor environments. SkyWalker's primary interaction method with user is voice control, where a user control the robot using voice commands. The robot can also be teleoperated using a joystick as well.

7.2 Conclusion

SkyWalker is an assistive device to support the walking and STS motions of elderly persons. The thesis presented the mechanical and hardware design of the walker. The walker's design and size allow it to be accessed in different environments. The shell design and the walker's colour are chosen based on the literature review to ensure the walker is aesthetically pleasing to our target population. The robot went through many development stages to ensure that it is functional and can be used as a useful tool to help people in their daily lives. We looked into different assistive devices, including wearable and external devices that are either passive or active to understand the tools used to help people stand up and walk. In addition, we consulted geriatric clinicians on how users should stand up safely when applying load on the hand. We also improved on the mechanical design after conducting experiments and observing design limitations. For our software, we are using docker and ROS, which allow for easy software integration on a new device. It avoids problems related to software dependency conflicts. The robot can understand the user's intentions using voice commands. Alexa Echo dot three has been implemented in our design as an additional modality for human-robot interaction. We conducted an interaction study to observe how the device would perform during STS action.

Multiple studies have been done on the walker with healthy subjects to test the functionalities and the safety of the device before using it with older adults. The studies looked into the kinematics and kinetics of the human body when using SkyWalker, as well as the feedback from subjects using modified RTLX and a custom survey. The results show that the user's height affects the forward travel distance during STS, and the trajectory period should not be more than 5 seconds. A large forward travel distance can affect the user's balance during STS action, which could lead to a fall. Small forward travel distance can put the upper body on greater physical demand while keeping the knee joint in a not fully extended position for a longer period. For walking trials, the robot has been tested in indoor and outdoor environments. The robot was teleoperated using a joystick, and the subjects were asked to follow the robot. The height of the upper handles was adjusted to the user's preference. The subjects had to go around obstacles and walk on different terrains. For turning, the subjects preferred an on-wheel turn as the robot was smoother and had to do less movement than an on-spot turn. On-spot turn was better for environments with a small amount of space.

For STS trajectories, we had a problem tuning the velocity controller of the robot. The robot did not generate the desired path by generating a linear STS path instead of an S-curve path.

For future work, several experiments are planned to address the shortcomings of the preliminary evaluation in this paper: more participants with different heights and body weights are required, in particular participants from the elderly population, to get a better understanding of how the handle trajectories can be improved.

7.3 Limitations and Future Work

Despite the successful design and construction of SkyWalker, many things need to be implemented and improved on SkyWalker. Mechanically, we need to compare one-level handles to two levels handles to understand which option the users prefer. Another version of SkyWalker is currently in planning with the same functionalities but more accessible and aesthetically pleasing.

An essential piece of work is improving the velocity controller on SkyWalker. This can be done by re-tuning the PID parameters. This will allow us to test different types of STS trajectories. Moreover, model-based simulation and optimal control will be used to support the determination of the best possible trajectories. The initial testing has been done with linear trajectories.

The robot has not yet been validated with older adults with mobility impairment. It should be done as soon as possible to check if SkyWalker provides assistance and whether it needs to be redesigned. SkyWalker should be tested at senior homes and with people who need assistance to see if the device works in an actual life situation that might not come in an in-lab testing environment.

We need to investigate the optimal interface to allow the user to control the direction and movement of SkyWalker independently. One possible interface is voice control implemented using Echo dot 3. An interaction study has been done for STS, however we still need to test voice control while walking with SkyWalker. Moreover, Echo dot 3 has eight different lights and animations shown in figure 7.1. We need to investigate if we can use the lights to interact better with the users and act as a safety feature. Experiments need to test different voice control commands in order to determine which words are easier and more intuitive for controlling the walker.

Finally, forces on the handles where the user is grabbing the walker will be recorded, along with the forces the feet are experiencing. Last but not least, the planned validation studies with the target population will be conducted.

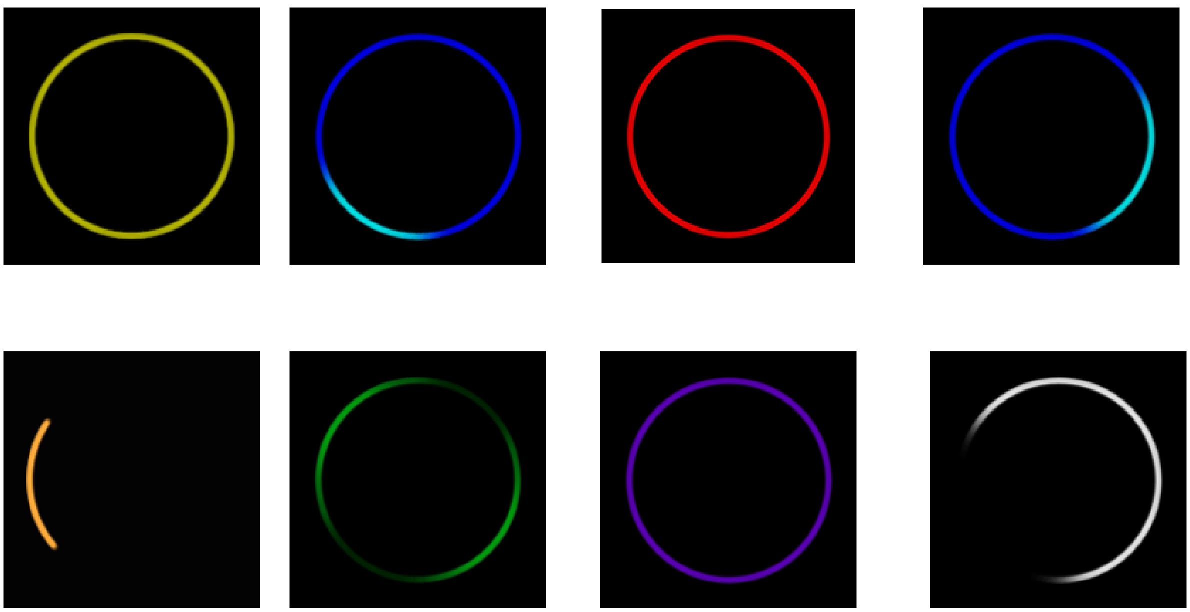


Figure 7.1: There are different colors and animations Alexa echo uses to communicate with users. For example, Cyan on blue light means that Alexa is listening and can pin point where the sound is coming from by pointing the cyan color in the sound direction as shown in the image. Color red means Alexa is not Listening

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