Evaluating the Effectiveness of a Stair-Assisting Bench in Enhancing Mobility for Patients with Below-Knee Injuries

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Abstract

Thousands of physical therapy patients suffer from lower leg injuries, necessitating assistance when climbing stairs. Current short-term solutions, such as crutches or hands-free crutches, are primarily designed for flat ground use and are not suitable for stairs. A novel device is being developed to address this gap by incorporating safety measures tailored for stair use. This study seeks to justify design decisions related to ergonomics and device dimensions based on patient anatomy. The research is designed to provide critical insights into the device's design, with measures in place to obtain IRB approval. This approval has influenced the selection of methods for this single-center study, which analyzes data from five subjects. The study primarily focuses on qualitative results obtained through a questionnaire administered to test subjects. The questionnaire provides insights into user experience, particularly regarding various use cases such as injuries stabilized with a boot or those healing without a cast, while being compared to those same use cases with the other devices. The secondary focus is to assess the stability of the interventions via analysis of postural control measures. With desirable results, there can be advancement in the development of a market-ready device to address the unmet need for safe and convenient in-home stair climbing for individuals with lower leg injuries. The validated device could be prescribed by physical therapists as a more user-friendly solution, potentially reducing the risk of reinjury or accidents associated with unsafe devices.

Introduction

From 2016 to 2020 hospitalization for lower extremity injuries increased from 130,000 to 180,000 patients accounting for 13% of all emergency department admissions [1]. Most of these patients require rehabilitation for injuries sustained and will have a period of non-weight bearing for proper healing. The non-weight bearing period can last for 4 to 6 weeks or longer depending on the severity of the lower extremity injury [2]. Medical professionals readily prescribe helpful tools like crutches, canes, scooters, and wheelchairs to assist in navigating daily activities within the home while recovering; however, these can still present significant challenges [3].

A major hurdle for these individuals is the lack of readily available and reliable solutions for traversing stairs. While ramps and elevators may exist in certain settings, within the typical home environment, these options are often impractical or even nonexistent. This creates a significant gap in accessible home mobility solutions, hindering patients' ability to navigate their living space safely and comfortably during their crucial recovery phase. Standard axillary crutches are the most commonly prescribed ambulatory assist device used to maintain weight-bearing

restriction. While crutches are an optimistic solution for some individuals there is a prevalent risk of overuse injuries, arm and shoulder strain, fatigue, inconvenience, and falls [3]. Crutches restrict upper extremity use and hinder balance which poses a greater challenge for traversing stairs [4].

Figure 1. Standard axillary crutches [5]

A commercially available alternative to standard crutches is the iWalk, a hands-free crutch (HFC) [6]. This ambulatory assistive device attaches to the thigh and lower leg with a bench to support the lower leg in the bent position and frees the upper extremities for use. This hands-free assistive walking device can reduce the fall risk and allow for increased balance during ambulation on level surfaces. However, the iWalk is cumbersome and inconvenient to use while traversing stairs.

Figure 2. iWalk hands-free crutch (HFC) [6].

An alternative method for stair climbing involves using a simple garden bench. This approach utilizes a compact plastic box placed on the step, allowing the patient to rest their knee while adjusting their other leg to ascend. This solution offers convenience and affordability. However, concerns regarding safety and usability emerge. During stair ascent a second person is needed to reposition the box after each step or the patient must use one hand to move it, potentially compromising stability by reducing points of contact.

Figure 3. Plastic garden bench [7]

Our novel solution to stair climbing is the Stair assist bench (SAB). This device provides support to the non-weight bearing leg while climbing stairs. The SAB is incredibly versatile, capable of seamlessly adapting to the needs of both left sided and right sided non weight bearing individuals, ensuring comfortable and efficient use for all users. The bench has a flat base, adjustable central column, leg platform, leg cushion, and handle. The adjustable support column allows for device height to be changed in 1 inch increments from 12 inches to 18 inches tall. Device is free standing and independently operable using the front handle.

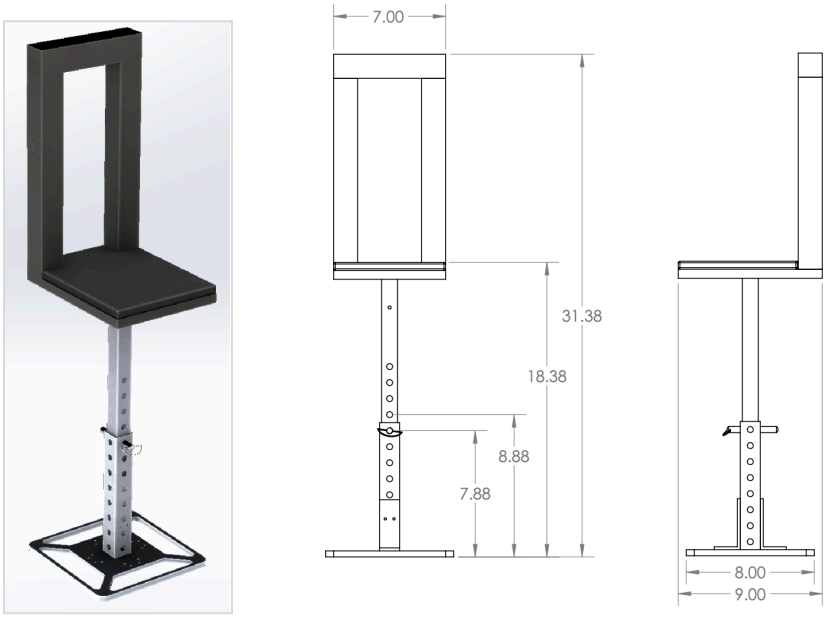

Figure 4. Stair assist bench (SAB) diagram and CAD measurements.

Addressing this gap in accessible home mobility solutions is crucial for improving the quality of life and recovery prospects for these patients. By fostering the development of innovative and home-friendly mobility aids, we can empower individuals to move around their own homes with greater ease and confidence, ultimately facilitating a smoother and more successful recovery journey.

Postural stability is the ability to maintain balance while performing a task. Traditionally, postural stability has been assessed by spatial measurements of the center of mass (COM) and center of pressure (COP) [8,9]. The center of mass is where the weight force of the human body acts while the center of pressure is the resultant application of ground reaction force (GRF). Postural instability is associated with greater COM or COP displacement.

Objectives

The primary purpose of this study is to compare COP of stair assist device use (NONE, SAB, and HFC) and fracture boot use on stair climbing in a group of healthy, able-bodied participants. Firstly, it was hypothesized that the stair climbing using the HFC will have greater COP displacement compared to the SAB. Secondly, it was hypothesized that both stair assist devices (SAB and HFC) will have greater COP than walking without an assistive device (NONE).

The secondary purpose of this study is to compare stair climbing effects of the stair assist devices (SAB and HFC) with fracture boot use on participant comfort, pain score, and device preference. It was hypothesized that participants will have increased comfort with the use of the SAB, and no difference in pain score between the SAB and HFC devices. Additionally it was hypothesized that participants prefer the SAB over HFC during stair climbing.

Methods

Participants

The team, consisting of five injury-free subjects ages 21-22, were the participants in this study. The testing took place in the Engineering Centers Building, Lab 1002, and lasted two hours.

Testing Methodology

Interventions

The first intervention was a control without a device. The second intervention was the stair assist bench (SAB) for which its effectiveness was investigated. The third intervention was the hands-free crutch (HFC) for comparison to the SAB.

Protocol

Participants underwent a physical examination to obtain their weight and height to ensure they qualified for the study. The participants were asked to wear a fracture boot to emulate a non-weight bearing injury that is distal to the knee. Two cinder blocks were placed side by side on one force plate to account for the dimensions of a realistic stair step, and another cinder block was placed to the right, not in contact with the force plate for the other foot.

Each participant ascended one step and descended one step with the three research conditions in the respective order: 1) NONE, 2) BOOT + SAB, 3) BOOT + HFC. After completion of the experiment, participants were asked to fill out a feedback form that included pain ratings, comfort scores, device preference, and further feedback on the device.

Figure 5. One-step stair ascension experimental setup. Each participant performed three trials each for three conditions: Control (top left), Stair-Assist Bench (SAB) (top right), and the Hands-Free Crutch (HFC) (bottom). A force plate was used to collect center of pressure (COP) measurements to assess postural stability.

Monitoring and Auditing

One team member used the SAB prior to testing and made appropriate modifications to mitigate risks before commencing the participant study. Throughout the study, the team closely monitored the structural integrity of the device and ensured all participants felt safe, ensuring that no undue risks were encountered and retaining the authority to halt any trial if safety concerns arose.

Outcome Measures

Outcome measures were computed based on verbal periods indicated by the subjects, who verbally signaled the start and end of the trial coinciding with the initiation and completion of a one-step stair ascent. A typical example of the stabilogram for a participant performing all three interventions from which outcome measures were extracted, is illustrated in Appendix B. Postural stability outcome measures were calculated, including six parameters representing various time-domain center of pressure (COP) measures in the horizontal plane. All COP measures incorporated components in both the anterior-posterior (AP) and mediolateral (ML) directions.

Postural stability is represented by three dimensions: stability performance, control demand, and postural regulations (see Table 1). The COP measures, comprising distance and area measures—estimate the displacement and velocity of the COP, related to stability performance and control demand, respectively. An increase in control demand has been linked to a higher reliance on visual inputs for maintaining postural stability and an elevated risk of falling [10]. Consequently, a decrease in stability performance (increased COP displacement) coupled with increased control demand (increased COP velocity) is interpreted as reduced postural stability. A hybrid measure combined distance measures and velocity to quantify the relationship between control demand and stability performance.

Types of Measure	**Outcome measures**	**Description**	**Interpretation**
Time-domain distance measures	MDIST (cm)	Average distance from the mean COP	Indicators of stability performance
	TOTEX (cm)	Total length of the COP path	
	RANGE (cm)	Maximum distance between any two points	
	MVELO (cm/s)	Average velocity of the COP	Indicators of control demand
Time-domain area measures	AREA-CE (cm^2)	95% confidence ellipse area	Indicators of stability performance
Time-domain hybrid measures	AREA-SW (m^2/s)	Sway area	Indicators of the relationship between control demand and stability performance

Table 1. Summary of the COP outcome measures.

Each intervention’s functionality was assessed using a numerical pain rating scale, a comfort score for the device, and a device preference score. Associated pain refers to any discomfort or pain that patients experience directly due to the use of the intervention. This pain is quantified on a numerical scale from 1 to 5, where 1 represents no pain. Device comfort measures how comfortable patients feel while using the intervention. This encompasses various factors, including the ergonomic design of the device, its padding and supports, and the overall user experience. High comfort scores suggest that the device is well-tolerated and meets the users' needs effectively. Device preference indicates which intervention the users favor. COP measures were used to interpret the patients' feedback, offering insights into how the intervention might influence feelings of unsteadiness during stair transit.

Statistics

Statistics for all COP measures across all interventions (SAB, HFC) were calculated to analyze their effects on stability performance. A one-way ANOVA for independent samples, with a within-subject factor of control versus device intervention, was performed for each COP measure to determine if significant differences existed across groups. Significant interactions were identified with p-values less than 0.05.

One-way ANOVA was used to access participant-reported outcomes, including pain ratings, comfort scores, and device preferences [11]. Statistical significance was set at $p < 0.05$. This statistical approach enabled the visualization of the relationship between the reported individuals’ balance confidence and the characteristics of stair ascension stability.

Ethics

The team performed all testing on ourselves eliminating the need to file for human testing. No form of consent was needed as all members had full knowledge of the test and the device prior to accepting the test.

To safeguard the confidentiality of participant data, strict measures were implemented. Firstly, all data was coded, and the corresponding "key" linking identities to codes was securely stored separately from the data itself. Moreover, data stored on portable devices were also coded, with the key kept in a separate location to prevent unauthorized access. No identifiable information was retained on portable devices to further mitigate risks. Additionally, identifiers were promptly destroyed either at the closure of the study or upon publication unless proper consent is received for the use of participants' lower body in future video presentations to uphold their privacy. Consent was obtained from the consent form filled out before participation. Procedures were conducted in a private area, ensuring that others cannot observe the activities or overhear conversations between subjects and researchers. Furthermore, height and weight information may be shared, as they were collected to ensure the participant is within the constraints of the

SAB. These measures collectively uphold the confidentiality and privacy of participant data throughout the research process.

Funding

Funding is coming from an outside client, Dan Kutschera. Dan is a local Wisconsin physical therapist who informed the team of the lack of innovation to assist patients in navigating stairs after lower leg injuries. He may only review the questionnaires and videos demonstrating SAB usage from the waist down, provided that consent is obtained.

Results

All COP measures calculated for each intervention are summarized in Table 2, as well as within-group comparisons. TOTEX, MDIST, MVELO, RANGE, AREA-CE, and AREA-SW measures were the COP measures to be significantly different between the Control and SAB groups. Stronger statistically significant differences ($p<0.001$) were found among stability performance measures in comparison to the control demand measure (MVELO). MDIST was the only COP measure to be significantly different between the Control and HFC groups. Figure 6 visually presents the SAB and HFC measures from Table 2 relative to the control condition. All measures are normalized to percentage values, with the control group set at 100%.

Table 2. Mean ± standard deviations for COP measures across groups with statistical significance indicators.

	Control	SAB	HFC	SAB vs. Control	HFC vs. Control
TOTEX (cm)	261.65 ± 91.71	1256.71 ± 1166.99	396.89 ± 344.00	*	
MDIST (cm)	1.81 ± 0.47	4.54 ± 1.30	2.38 ± 0.67	***	*
MVELO (cm/s)	140.80 ± 65.15	428.44 ± 281.71	145.63 ± 89.54	*	
RANGE (cm)	43.77 ± 26.98	94.82 ± 38.94	33.41 ± 31.27	**	
AREA-CE (cm)	43.75 ± 14.79	318.06 ± 153.56	73.31 ± 43.43	***	
AREA-SW (cm^2/s)	140.72 ± 88.27	428.29 ± 369.36	145.57 ± 144.95	**	

Asterisks (*) indicate statistically significant differences (=$p < 0.05$, **=$p<0.01$, ***=$p<0.001$) compared to the control group, as determined by one-way ANOVA tests indicating a significant main group effect. SAB: stair-assist bench; HFC: hands-free crutch.*

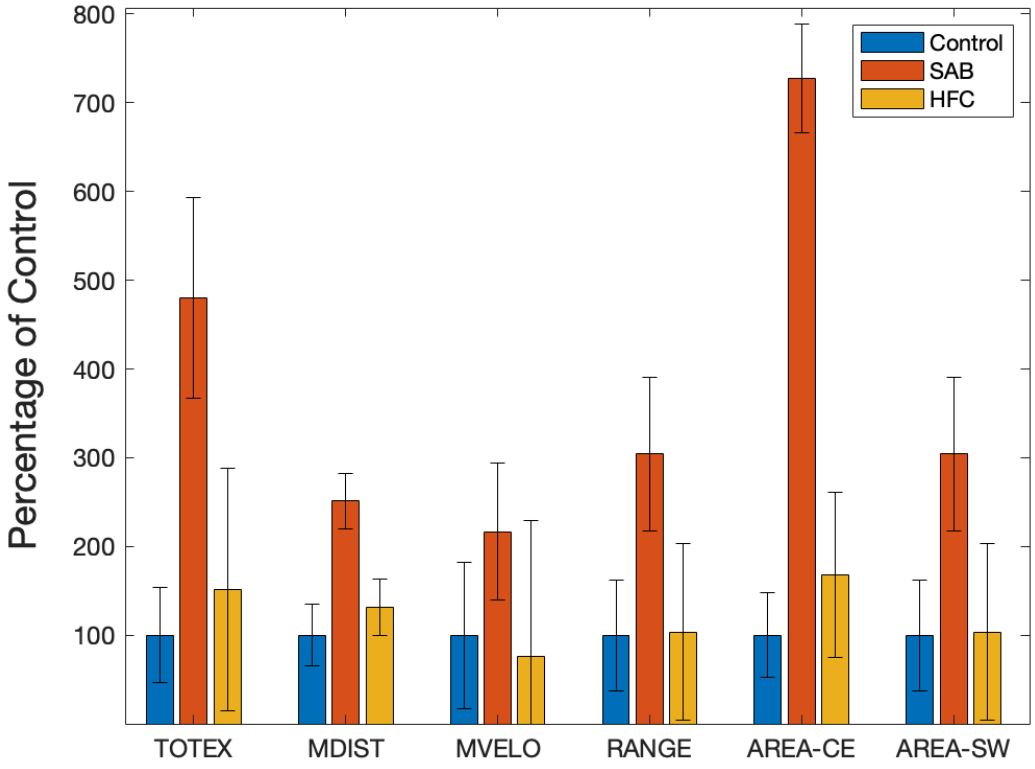

Figure 6. Control, SAB, and HFC interventions for each COP measure. SAB and HFC normalized to percentage values based on the Control group.

The device preference, associated pain, and device comfort were quantitatively evaluated based on participant feedback (see Appendix C). To calculate these metrics, the scores provided by all participants for each category were aggregated. Each score was then divided by the maximum possible score that could be obtained if all participants had given the highest possible rating. This quotient was subsequently multiplied by 100% to convert it into a percentage, providing a normalized measure of each metric across all subjects.

Table 3 presents these calculated percentages for the SAB and the HFC. The device preference scores show a strong favorability towards the SAB, with 100% of participants preferring it over the HFC. In terms of associated pain, the results indicate a slightly lower pain score for the SAB (44%) compared to the HFC (48%), suggesting that the SAB may be associated with less discomfort. Additionally, the device comfort scores were significantly higher for the SAB at 92%, compared to 72% for the HFC. Comparison of the SAB with the HFC yielded significantly different ($p<0.05$) comfort scores and device preference scores.

Table 3. Normalized measures of device preference, associated pain, and device comfort: comparative analysis of participant responses for SAB and HFC.

	SAB + BOOT %	HFC + BOOT %	SAB vs. HFC
Preference	100	0	*
Associated pain	44	48	
Device comfort	92	72	*

Asterisks (*) indicate statistically significant differences (=$p < 0.05$) of the SAB compared to the HFC, as determined by one-way ANOVA tests. SAB: stair-assist bench; HFC: hands-free crutch.*

Discussion

The purpose of this study was to determine the effect of the SAB and HFC with boot use on COP during stair climbing, as well as participant reported comfort, pain score, and device preference in healthy able bodied participants. COP measures of TOTEX, MDIST, MVELO, RANGE, AREA-CE, and AREA-SW were found to be significantly different between the Control and SAB groups. The larger COP measures indicate less postural stability while using the SAB compared to normal stair climbing. MDIST was the only COP measure found to be significantly different between the control and HFC groups. This indicates that postural stability while using the HFC was similar to that of normal stair climbing. These findings do not support the first hypothesis that stair climbing using the HFC will have greater COP displacement compared to the SAB. However, these results partially support our hypothesis that both stair assist devices (SAB and HFC) will have greater COP than walking without an assistive device (control). The MDIST measurement of COP was found to be significantly greater in SAB and HFC than the control. This study assumed that greater COP measures were linearly related to increased postural stability. However recent postural control studies suggest that there may be greater physiological complexity to the fluctuations in COP [12]. Current measures ignore the dynamic characteristics of COP movement and do not represent more subtle aspects of postural control [13]. In the future COP fluctuations can be addressed through detrended fluctuation analysis (DFA) and Hurst rescaled range analysis to assess the validity of COP and postural control.

The results of the participant feedback questionnaire showed a 100% device preference for the SAB, higher device comfort with the SAB, and no statistical significance for associated pain between SAB and HFC. These findings support our secondary hypotheses that participants will have increased comfort with the use of the SAB, no difference in pain score between the SAB and HFC devices, and a preference for the SAB during stair climbing. Participant questionnaire data suggests that users felt more comfortable using the SAB and preferred this device over the HFC. However, the participant feedback is inconsistent with the COP results that indicate the HFC had more postural stability consistent with control conditions for stair climbing. The

contradiction in COP measures and questionnaire results requires future testing with a larger sample size to remove testing bias.

Factors such as injury location, weight-bearing status, balance, and patient preference play crucial roles in selecting the right assistive device for stair climbing. Considerations such as balance confidence and comfort can impact an individual's ability to safely ascend and descend stairs. The study participants favored the SAB over the HFC but showed improved balance with the HFC when wearing a walking boot according to COP measures. The SAB required more adjustment in postural stability while using the device to climb stairs. These findings demonstrate that personal device preference and assistive device stability are important factors to consider when choosing a non-weight-bearing support device following lower leg injuries.

Limitations

Limitations of this study should be considered when interpreting the results. This study focused on the postural stability of stair climbing with the SAB and HFC based on COP, however only one step was assessed. The stair model was replicated using cinder blocks that adhered to OSHA stair guidelines for stair riser height but not tread depth. This study looked at a small sample size of 5 healthy individuals ranging from ages 21 - 22 with limited height variability and familiarity with both devices prior to testing. Testing only analyzed stair climbing assistive devices for postural stability but not a biomechanical analysis using joint moments and angles with motion capture. The study compared two unique stair assist devices but no comparison was made to standard axillary crutches. Future studies should consider larger participant groups, multiple stairs, motion capture kinetic and kinematic analysis, and other stair assist devices. Evaluation of devices on different stair surfaces should also include standardized time analysis.

Conclusion

This study demonstrated that the SAB was a reasonable alternative to other stair assistive devices for non-weight bearing individuals with below-the-knee injuries, but requires improvement to be commercially ready. This design is a prototype and the diversity of materials used exemplifies this. The team would like the final design to be fully aluminum to reduce weight and make the whole design more rigid. The center of pressure of the user moves more with the SAB than both the control and the HFC meaning the SAB will need to improve its base stability to help the user balance. This can be achieved by creating a permanent connection between the telescoping pole to the base; in addition, the telescoping poles can become more flush leaving less wiggle room and a greater connection between the two pieces of the device. In the limiting testing completed, the SAB demonstrated patient preference, perceived exertion, and physiological demand compared with other assistive devices in healthy, able-bodied individuals. The SAB would benefit greatly from a larger test with more diverse testing subjects. This research is the first validation study using the SAB; however, further research is needed to help establish clinical practice guidelines.

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Appendix A

Design Process

Goal Evaluation and Prototyping

The design process for this device involved several steps, reflecting an approach to achieving a stable, user-friendly, durable, and cost-effective device. The initial design phase involved defining the key functionalities and performance criteria that the device needed to meet. This included considerations for weight, durability, cost-effectiveness, and specific use-case scenarios. Early in the process, materials for the device were selected based on their properties and the requirements of the project. T6061 aluminum alloy was chosen for the base due to its workability, lightweight nature, and corrosion resistance. Cedar wood was selected for the initial prototype framework considering its availability, cost-effectiveness, and structural integrity.

The first stage of prototyping involved creating a wooden framework to evaluate the design's overall structural integrity. This prototype employed 2x2 by 8-foot long cedar wood planks, joined together using wood screws. This step allowed the team to physically assess dimensions, weight, and stability. The design incorporated a two-bar handle to distribute mass away from the pivot point, increasing the moment of inertia and resistance to rotational motion, thereby improving stability. The base was designed as a 3x3 square, with a screw securing the support column through the center of the wood. Four rubber stoppers were positioned at each corner to prevent slipping and accommodate the slight warping of the wood, ensuring it remained stable when it didn’t sit flush to the floor.

Final Iterations

Modifications to the design were implemented following the team's testing of its functionality. A foam topper was added for comfort, and an aluminum base was designed to replace the original wooden base, aiming to enhance stability and durability. The design of the aluminum base was refined using SOLIDWORKS, where a model of an 8x8 inch square frame featured a hollowed cavity to maintain lightness while improving the moment of inertia for better stability. The aluminum base was combined with the remaining parts of the prototype, including the wooden structure and foam topper. L-brackets were used to further enhance stability where the support column joined with the base.

Experimental Design

Testing Methodology and Protocol

The testing protocol aimed to evaluate the device's stability criteria through force plate testing analysis. A force plate is an instrument designed to measure forces exerted on it in three dimensions. This platform consists of a sensitive, flat surface that captures ground reaction forces when an object or person stands or moves on it. The force plate testing facilitated the collection of data related to the Center of Pressure (COP). COP refers to the point where the resultant force vector acts upon the force plate's surface. This is essentially the location of the applied forces. Analyzing the COP data enables a better understanding of the balance and stability of the tested device.

Each trial was conducted using a force plate located in the Engineering Centers Building BME laboratory. The device was placed centrally on the force plate. A subject suitable for the device based on their tibial measurements placed their right knee on a bench as part of the device, ensuring the right foot was elevated and not touching the force plate while the left foot remained beside the force plate for stability. This arrangement meant that only the forces exerted by the right knee were measured. With the subject maintaining a rigid posture and remaining still, the force plate recorded the ground reaction forces continuously for ten seconds. Measurements were taken in both anterior-posterior and medial-lateral dimensions. This process was repeated for three trials with each base type (wood and aluminum), capturing the variations in forces that reflected the subject's postural adjustments.

Force Plate Data Analysis

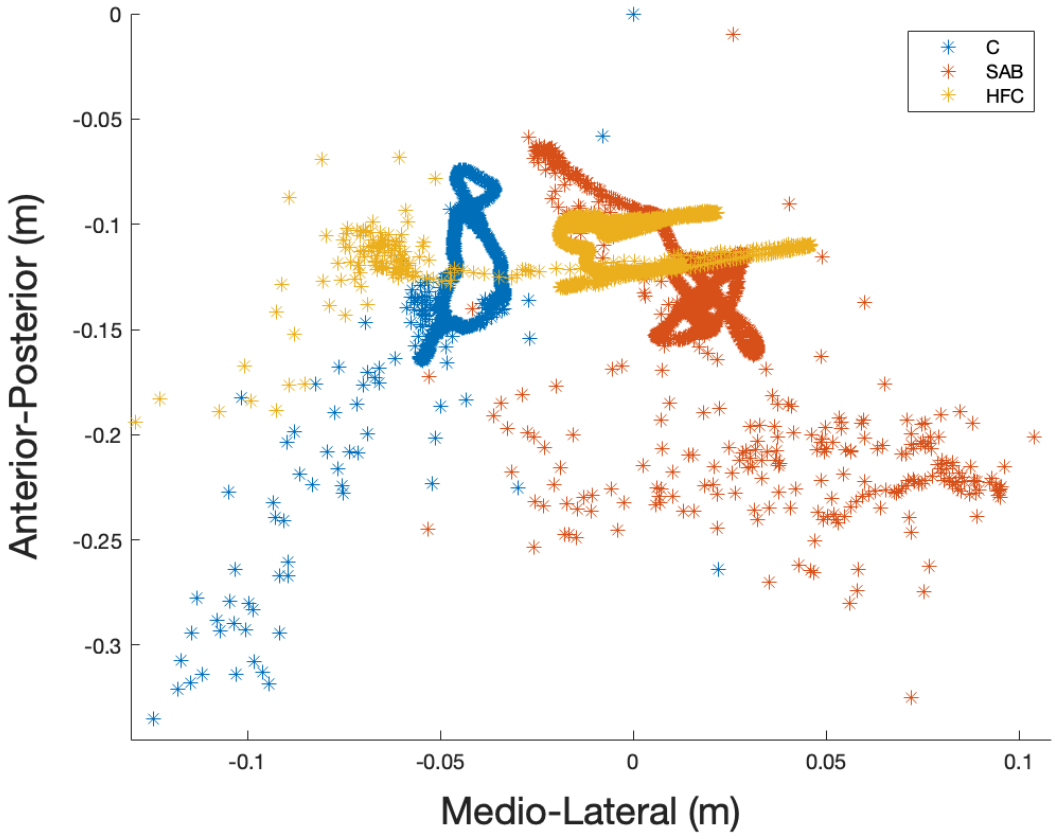
The collected COP data was analyzed using MATLAB to create stabilogram graphs. These graphs visualized the movement of the COP during each trial, representing the subject's balance adjustments. Further analysis included looking at the COP magnitude of displacement and the COP path length for each base. The magnitude of displacement was analyzed by enclosing all COP trace points on the stabilogram within a rectangle, with the area of this rectangle indicating how much the COP moved. A significant difference in the mean COP magnitude of displacement between the aluminum and wood bases suggested that the aluminum base better minimized postural control oscillations. Another assessment was the COP path length, representing the total distance the COP moved, provided insights into the activeness of postural adjustments. While the analysis of path lengths did not show a statistically significant difference between the two base types within the small sample size of this study, it suggested potential areas for further investigation.

Conclusion and Results

The results concluded that the aluminum base had superior performance by effectively minimizing oscillations, thereby enhancing the device's stability. Following testing, there were

several areas of improvement and refinement needed to enhance the design, usability, and safety of the device. Structural and material adjustments will be made to construct the device's framework out of aluminum to make it lightweight and durable. Additionally, the support column will be made adjustable to accommodate users of varying heights. Furthermore, a more comfortable pad for the bench will be designed to improve user comfort. After further prototyping with these considerations in mind, testing will be conducted. This testing phase will involve a group of users utilizing the device, and the feedback gathered will be used to refine the device and ultimately evaluate its effectiveness, safety, and comfort.

Appendix B



Stabilogram depicting the COP trajectories during a one-step stair ascent performed by a single subject across three interventions.

Appendix C

Pain rating SAB	Comfort score SAB	Pain rating HFC	Comfort score HFC	Device preference (1=SAB, 2=HFC)

3	4	2	3	1
2	4	3	4	1
2	5	2	3	1
2	5	3	4	1
2	5	2	4	1

Raw qualitative data from the participant feedback form post force plate testing.