

Mechanical Bracing Solutions to Decrease Tibial Slippage of Anklebot

by

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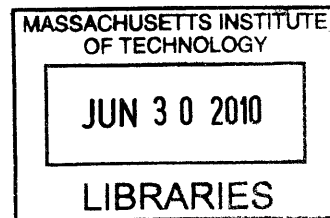
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ABSTRACT

Anklebot is a general-purpose therapeutic robot designed to guide the human ankle through motions with appropriate assistance. Anklebot relies on accurate position feedback from its actuators, which may or may not be corrupted due to slippage of Anklebot. This study seeks to quantify the slippage that exists using the current shoulder strap support system and seeks to identify new methods of support that warrant further investigation. An exoskeleton support system and a waist support system made of bungees attached to a belt were prototyped methods to improve upon the current shoulder strap design. Variance in the separation between markers on the knee brace and leg was used as a measure of slippage. The exoskeleton did not decrease slippage primarily due to high tolerances in the inversion-eversion joint at the heel of the shoe. The waist support system decreases slippage when enough bungees were attached. Further work on the waist support system is recommended.

Thesis Supervisor: Neville J Hogan

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1 Introduction

Anklebot is a general-purpose therapeutic robot designed to guide the human ankle through motions with appropriate assistance. Anklebot is made up of two actuators and a specially designed knee brace and shoes, both with attachment points for two actuators on the anterior medial and the lateral sides of the leg. This entire device is anchored on the knee brace that is assumed fixed to the leg. The actuators can act as a system of springs and dampers that use an impedance control scheme. This set of actuators has the unique ability of providing both position and force feedback, which are key inputs into the impedance controller. These sensing properties of Anklebot's actuators also make Anklebot a powerful platform to measure and discover new biomechanical properties of the leg for better therapy metrics.

Device slippage relative to the leg is a major problem when Anklebot is used in either of its capacities, data collection or assisting gait. The primary causes of slippage are the weight and inertia of Anklebot as well as perturbations by the actuators. As the device slides up and down the leg, a significant amount of noise is introduced into the controller's position input because the controller assumes that the knee brace and actuators are fixed relative to the tibia. Main sources of slippage include the elasticity of skin and underlying tissue and sliding of the knee brace over the skin. During typical use, Anklebot is held up by a shoulder strap that runs around the shoulder opposite Anklebot and attaches to the front of the knee brace with two hooks. This study seeks to first quantify the amount of slippage experience by Anklebot using the shoulder strap. Secondly, it seeks to improve upon the current support methodology by identifying new minimally constricting mechanical bracing solutions that will further decrease slippage from the current design.

2 Prototypes

Anklebot's main function is to sense the ankle's position and impedance and encourage proper patient motion by providing appropriate assistance. Thus, any added support device should not constrain a patient's motion. At the same time, the device should support the weight of Anklebot thereby significantly decreasing the shear forces on the skin. The goal is to develop and test prototypes on the proof-of-concept level to identify devices that show promise in decreasing slippage and warrant further design work.

2.1 Exoskeleton

The first approach sought to stabilize Anklebot by supporting the device from below by pushing up from the shoe. A primitive exoskeleton was created with pivot points to allow inversion-eversion (IE) and dorsiflexion-plantar flexion (DP), Fig. 1. An ankle gimbal attached to the shoe, Fig. 2, connects to the knee brace via two vertical supports that run along the tibia. Tibial rotation was constrained in this design; however, tibial rotation does not encompass a significant range of motion during walking. For simplicity no extra design elements were added decrease this constrain on movement.

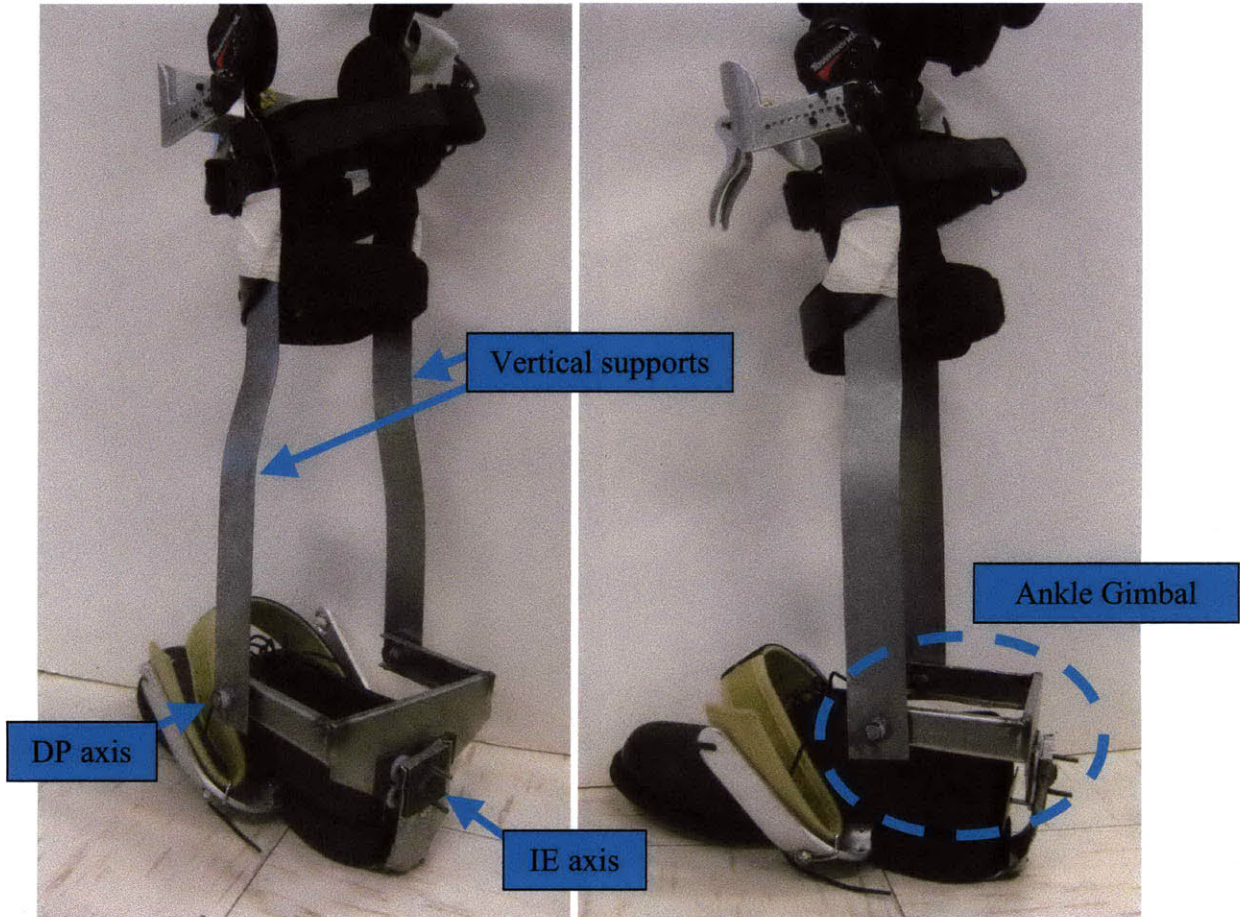


Figure 1 | Exoskeleton Prototype: Vertical supports run from the DP joint and are attached to the knee brace with athletic tape. The locations of the IE and DP axes were fabricated to specifically align with the subject's anatomy.



Figure 2 | Ankle Gimbal: The exoskeleton's ankle gimbal is attached to the shoe through four countersunk screws in the rubber heel of the shoe sole. Steel shafts and delrin bushings were used as the IE and DP axes.

2.2 Waist Support

The second approach supported Anklebot from above, similar to the currently used shoulder strap, using elastics anchored to a belt around the waist, Fig. 3. This design shortened the structural loop of the support device, which could decrease the change in walking gait produced by wearing the device. A climbing harness was used as a belt, and bungee cords of stiffness 10 N/m were used. Two to three bungees were looped through the belt's loops and hooked into points at the front and sides of the knee brace, Fig. 3.

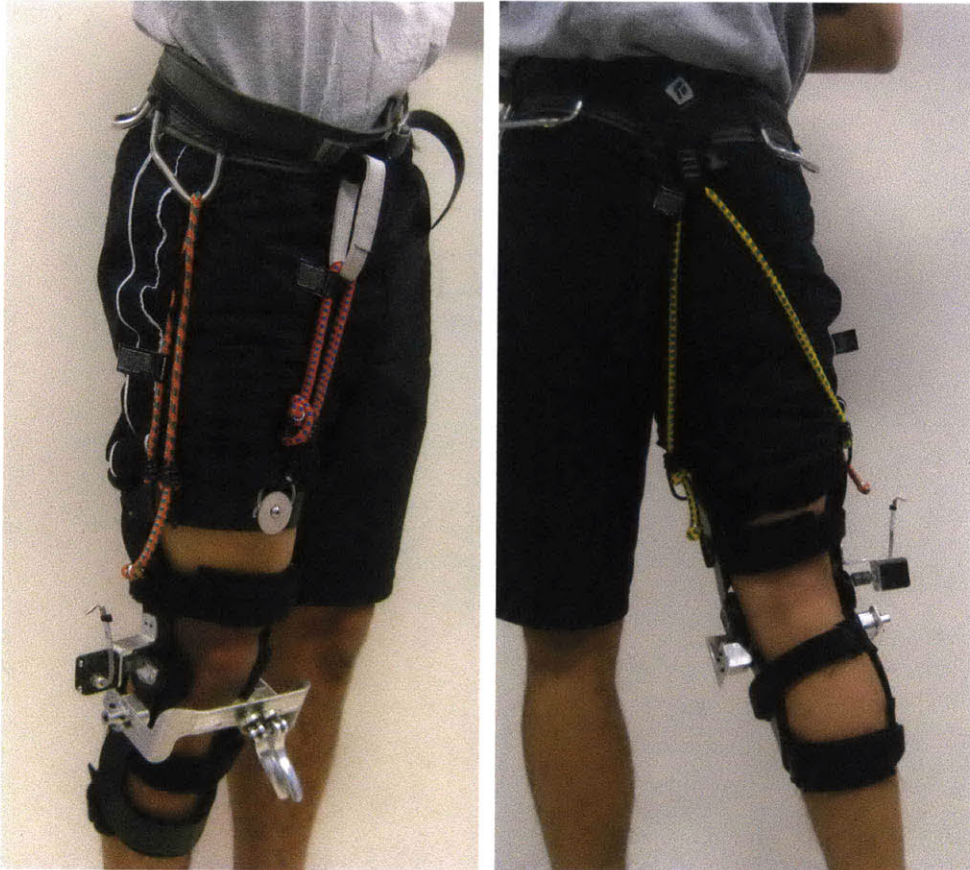


Figure 3 | Waist Support Prototype: A climbing harness and bungee cords were used to hold up the knee brace. Bungee cords were routed from loops at front, lateral, and rear positions of the belt to attachment points on the top portion of the knee brace. Bungee cords were either attached to the medial and lateral points on the knee brace or to a ring at the front of the brace.

Five different configurations were tested:

- 2 bungee cords, front loop to front ring and lateral loop to the lateral side of knee brace
- 2 bungee cords, front loop to both sides of brace and lateral loop to both sides of brace
- 3 bungee cords, all 3 loops to both sides of the brace
- 3 bungee cords, rear and lateral loops to both sides of the brace, front loop to front ring.
- 2 bungee cords, front loop to both sides of brace and rear loop to both sides of brace

3 Experimental Design

Experiments were performed with one subject wearing Anklebot and a support device while walking on a treadmill. A video camera recorded the positions of colored markers on the subject's leg and on the knee brace of Anklebot. The video was split up into individual frames and the centroid of each marker was calculated for every frame. The separation between centroid positions on the leg and on the knee brace was calculated for each frame. This process was repeated for every support method.

3.1 Marker Tracking

Video of a subject walking on a treadmill was taken from a lateral view at 30 fps. Each frame of the video was analyzed to find the centroid positions. Tracking of markers on the leg and on Anklebot's knee brace was implemented to determine their position. Yellow, green and blue markers were differentiated based on their RGB values. The brace markers, yellow and green, were adhered to the lateral side of the knee brace using double-sided foam tape. The leg marker, blue, was adhered to a lateral/anterior position approximately half way down the shin to minimize effects of disturbance by muscle contraction. The leg marker was assumed fixed relative to the tibia. A processed image was produced showing all the pixels fitting the criteria for blue, green, or yellow. Erode and dilate filters were applied to filter out small grains of noise. Their centroids, represented by gray squares in Fig. 4 were calculated by averaging all pixel positions of each color.

$$x_{centroid} = \frac{\sum_{i=1}^{N_{pixels}} x_{pixel,i}}{N_{pixels}} \quad (1)$$

A search box was also defined around the previous frame's centroid position to reject noise outside the search box.

3.2 Leg Frame

The line between the two dots on the knee brace approximated the angle of the leg throughout the gait cycle and was the basis for the leg coordinate frame, Fig. 4. The lower marker on the knee brace, green, was used as the origin of the leg frame. This frame rotated and translated with the leg through the gait cycle.

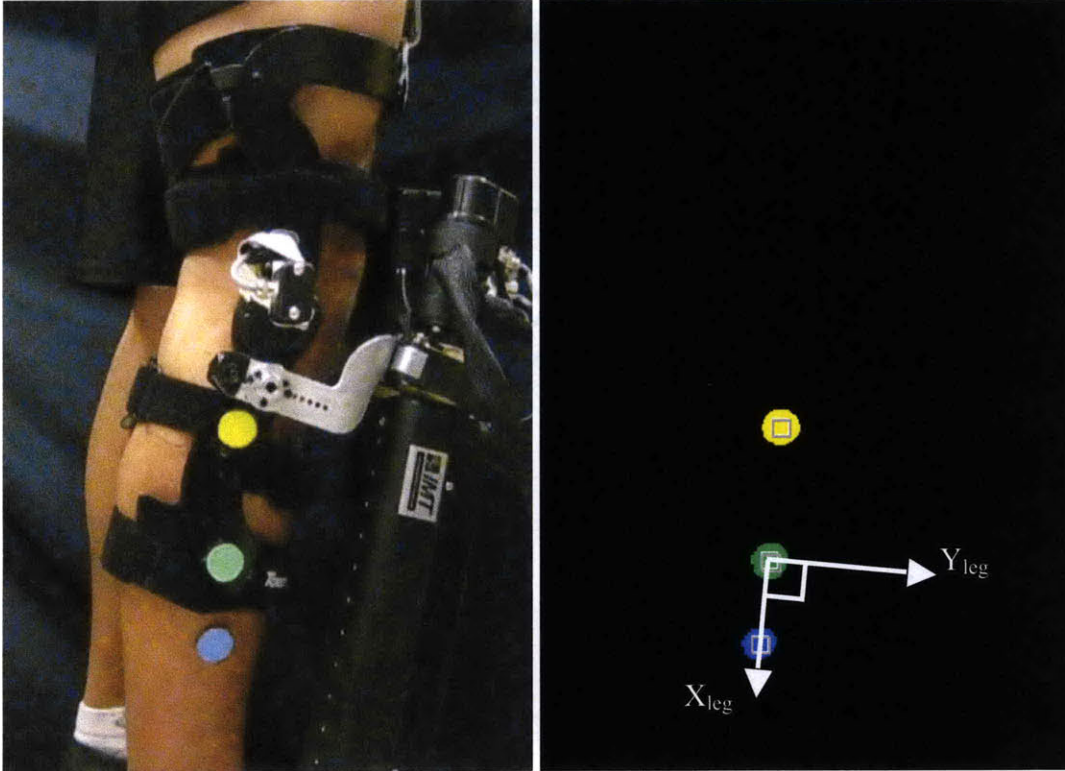


Figure 4 | Leg Frame: The raw image (left) was processed using the marker-tracking algorithm to produce the analyzed image (right). The x-axis of the leg frame is defined as the line between the green and yellow centroids, and the origin of the frame is the green centroid.

Separations between the leg and brace markers were simply the x and y components of the leg marker's position within the leg frame.

$$x_{separation} = x_{leg,blue} - x_{leg,green} = x_{leg,blue} \quad (2)$$

The leg marker was placed as close to the lower brace marker as possible to minimize error due to imprecision in the leg angle and to minimize motion of the dot from muscle contraction. Two markers used to extrapolate the leg angle were placed on the knee brace instead of placing two markers on the leg to minimize the angular error caused by motion of the skin due to muscle contraction.

3.3 Deviation from Calibrated position

Anklebot was “zeroed” during a calibration period lasting 2-3 seconds at the beginning of each trial. The calibrated $x_{\text{separation}}$ was the mean of $x_{\text{separation}}$ over the calibration period.

$$x_{\text{separation,calibrated}} = \frac{\sum_{i=1}^{N_{\text{calibration_frames}}} x_{\text{separation},i}}{N_{\text{calibration_frames}}} \quad (3)$$

Deviations from this calibrated position were calculated by subtracting the current dot separation from the calibrated separation along each axis.

$$x_{\text{deviation}} = x_{\text{separation}} - x_{\text{separation,calibrated}} \quad (4)$$

Deviations along the x-axis represent movement approximately along the tibial axis and deviations in the y coordinate represent movement perpendicular to the tibia. Deviations in x were the only ones considered important in this study since slippage along the x-axis has a direct effect on the length of the actuator. The resulting actuator displacement due to device slippage is almost all from deviations in the x-axis. Deviations in y, translations in y or rotation of the brace relative to the leg, are not considered important factors of slippage because those deviations have a smaller effect on the actuator shaft’s displacement.

The entire video was split into gait cycles at the point where the marker on the knee brace switched directions from moving forwards to moving backwards, very close to heel-strike. Only deviation values after the 5th cycle were used to ensure all data was from fully developed gait.

3.4 Trials

Control trials were run to both characterize slippage and provide a basis for comparison. These included trials of only the knee brace with no Anklebot and no support, the knee brace with no Anklebot and the shoulder strap, a passive Anklebot with the shoulder strap, and an active Anklebot with the shoulder strap. Trials testing the exoskeleton and the five waist support configurations were run with an active Anklebot. The active Anklebot’s impedance was set to a constant stiffness of 15N/m with no damping. The equilibrium position was set to the actuators’ position when the subject was standing, just before video calibration.

4 Results

Deviations from the calibrated position, $x_{\text{deviation}}$, were calculated for all frames of each trial and all data after the 5th gait cycle was plotted in histograms, Fig. 5. The Kolmogorov-Smirnov test was run for each distribution to test against normality (Rice 534). All samples showed non-normality, which subsequently limited the tests that could be chosen to compare variance and median between trials.

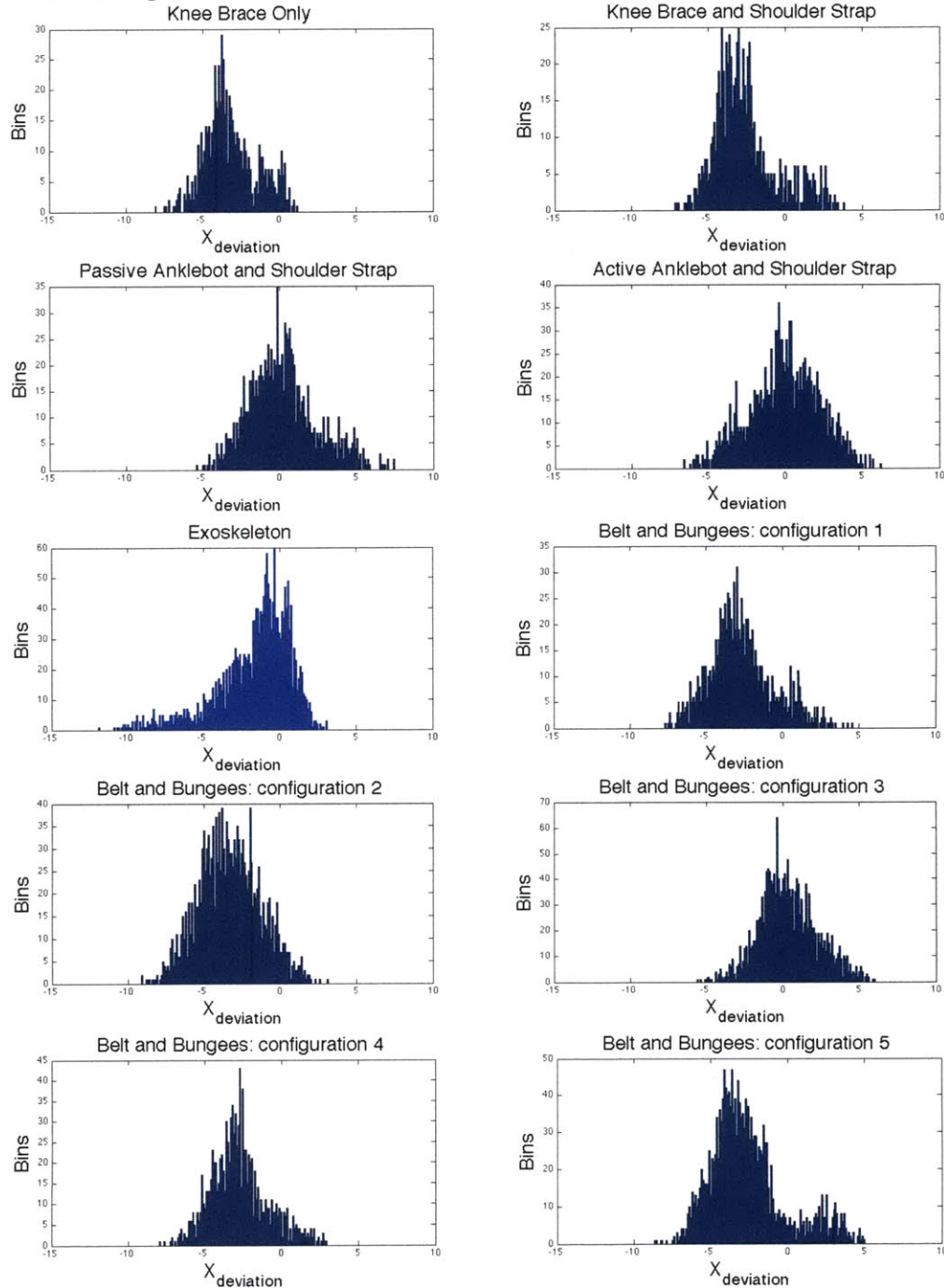


Figure 5 | $X_{\text{deviation}}$ Histograms: Deviation away from the calibrated separation length along the x-axis in mm.

4.1 Comparison of Variance

Variances in the $x_{\text{deviation}}$ distribution for each prototype support method were compared against variance for the shoulder strap support method using Levene's test, Fig 6. Levene's test is a one-way ANOVA that was chosen because it does not assume normality in the data. The null hypothesis for Levene's test states that the variances of two populations are equal, or in other words that homoscedascity is met (Rice 488). Homoscedascity was not met, $p < 0.05$, when comparing the active Anklebot with shoulder strap to the knee brace control and waist support configurations 2-4, meaning that these configurations exhibit less slippage than the shoulder strap support method, Table 1.

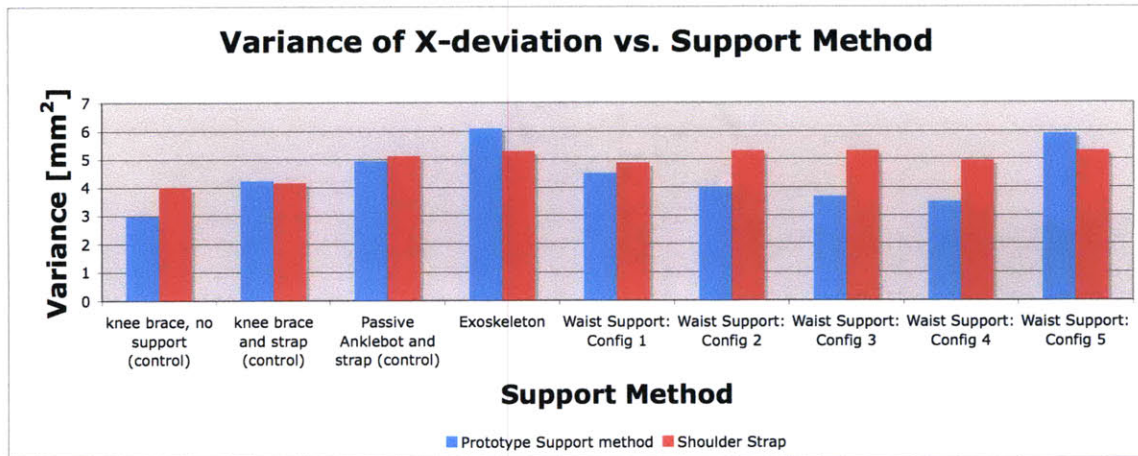


Figure 6 | Variance Comparison: Levene's test compared variance in $x_{\text{deviation}}$ between a prototype support trial and the active Anklebot and shoulder strap control. Prototypes (blue) with lower variance compared to the shoulder strap support method (red) are more effective at preventing slippage of Anklebot. Waist support configurations 2-4 and the knee brace with no support have significantly lower variances than the shoulder strap support, $p < 0.01$.

Table 1 | Levene's Test Results: Comparison of $x_{\text{deviation}}$ variance in the prototype support methods against the shoulder strap control with active Anklebot. The p value represents confidence in homoscedascity.

Trial	Trial Variance	Control Variance	P	Sample size for comparison
Active Anklebot and strap	5.29			1372
Knee brace, no support	2.99	3.99	0.02	692
Knee brace and strap	4.24	4.17	0.93	757
Passive Anklebot and strap	4.94	5.12	0.38	1112
Exoskeleton	6.10	5.29	0.20	1372
Waist Support: Config 1	4.51	4.87	0.18	991
Waist Support: Config 2	4.00	5.29	8.9E-06	1372
Waist Support: Config 3	3.68	5.29	1.3E-11	1372
Waist Support: Config 4	3.49	4.95	1.3E-08	1077
Waist Support: Config 5	5.91	5.29	0.77	1372

The variance of the control is slightly different between comparisons because Levene's test requires equal population sizes to run the comparison. The maximum sample size was used for each comparison.

4.2 Anklebot Position on Leg

The mean $x_{\text{deviation}}$ value for each trial showed how Anklebot shifted along the tibial axis relative to the calibration position, Fig. 7. The mean $x_{\text{separation}}$ was a measure of how high the brace settled anatomically on the leg between trials where higher values correspond to a higher position on the leg, Fig. 8.

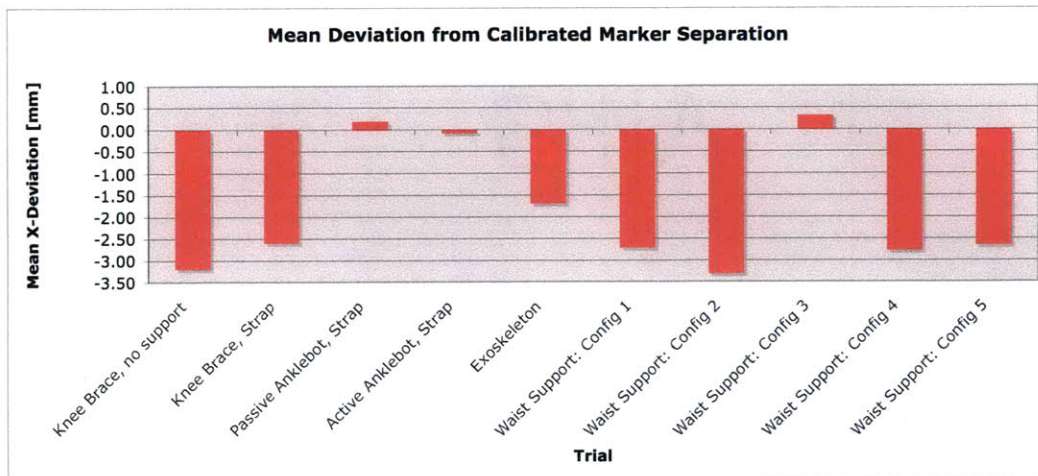


Figure 7 | Shift after Calibration: Mean $x_{\text{deviation}}$ from calibrated position. Negative values in mean deviation correspond to Anklebot sliding up on the leg after calibration. The shoulder strap support on both passive and active Anklebot as well as waist support configuration 3 did the best job of keeping Anklebot very close to the calibrated position.

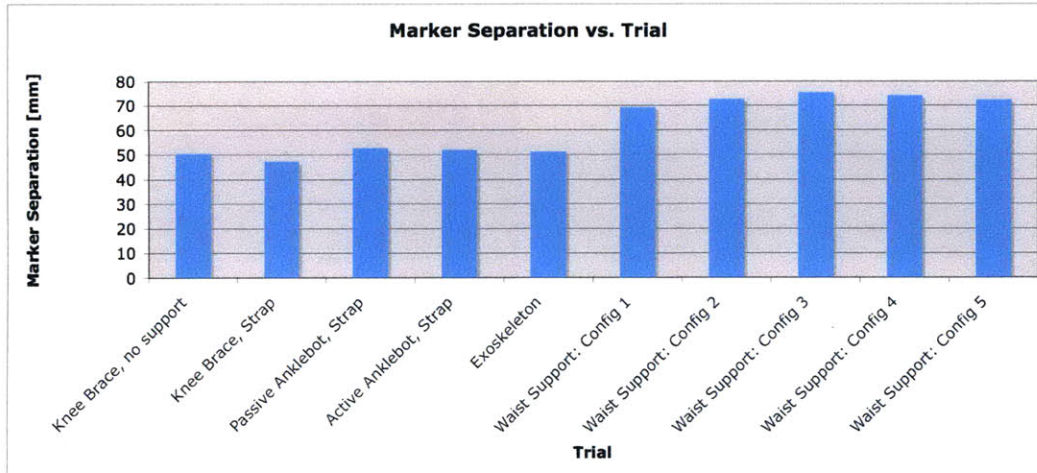


Figure 8 | Absolute Position on Leg: Mean Separation between the lower brace marker and the leg marker. Higher values mean the knee brace sits higher on the leg. All waist support configurations held Anklebot ~2cm higher than both the controls and the exoskeleton.

Table 2 | Anklebot's Absolute Position on Leg: Mean $x_{\text{separation}}$ and $x_{\text{deviation}}$ values for each trial are measures of Anklebot's absolute position on the leg and its shift relative to the calibrated position, respectively.

Trial	Mean $x_{\text{separation}}$ [mm]	Mean $x_{\text{Deviation}}$ [mm]
Knee brace, no support	50.41	-3.18
Knee brace and strap	47.31	-2.59
Passive Anklebot and strap	52.59	0.19
Active Anklebot and strap	51.91	-0.08
Exoskeleton	51.08	-1.69
Waist support: Config 1	69.16	-2.71
Waist support: Config 2	72.63	-3.31
Waist support: Config 3	75.56	0.32
Waist support: Config 4	74.18	-2.78
Waist support: Config 5	72.33	-2.65

4.3 Movement after Calibration

The Wilcoxon signed-rank test (Rice 320) compared the median $x_{\text{deviation}}$ value for each trial against a zero median, the calibration position, Table 3. This tested if Anklebot “settled” in a position that was shifted away from the calibrated position. All trials showed p values much lower than 0.05, meaning that in all trials Anklebot shifted away from the calibrated position.

Table 3 | Comparison against Zero Deviation: Wilcoxon signed-rank test compared each trial’s median $x_{\text{deviation}}$ to a zero deviation, the calibrated position.

Trial	p	h (p<0.05)	N samples
Knee brace, no support	3.0E-32	TRUE	692
Knee brace and strap	1.3E-29	TRUE	757
Passive Anklebot and strap	1.3E-10	TRUE	1150
Active Anklebot and strap	1.2E-49	TRUE	1372
Exoskeleton	1.5E-16	TRUE	1112
Waist support: Config 1	2.1E-140	TRUE	2017
Waist support: Config 2	2.7E-166	TRUE	991
Waist support: Config 3	7.2E-155	TRUE	1677
Waist support: Config 4	1.9E-86	TRUE	1839
Waist support: Config 5	1.7E-17	TRUE	1077

A second set of Wilcoxon signed-rank tests compared the medians of prototype trials to the median of the active Anklebot with shoulder strap control, Table 4. This tested if the amount of shift from the calibrated position for each prototype trial was different from the shift in the active Anklebot with shoulder strap control. Results show a significant difference in the mean values for all prototype trials, $p < 0.01$, except waist support configuration 3.

Table 4 | Comparison against Active Anklebot Control: Wilcoxon signed-rank test compared $x_{\text{deviation}}$ median for a prototype against the $x_{\text{deviation}}$ for the active Anklebot and shoulder strap control. True indicates that the null hypothesis can be rejected and the $x_{\text{deviation}}$ median is different from the control.

trial	p	h (p<0.05)	N_sample
Exoskeleton	2.52E-57	TRUE	1372
Waist support: Config 1	2.50E-101	TRUE	991
Waist support: Config 2	1.64E-169	TRUE	1372
Waist support: Config 3	0.060	FALSE	1372
Waist support: Config 4	8.32E-123	TRUE	1077
Waist support: Config 5	4.24E-127	TRUE	1372

5 Discussion

Levene's test comparing the knee brace alone against active Anklebot and shoulder strap showed a significantly greater variance in marker separation for the latter. The addition of Anklebot and the shoulder strap resulted in an increased slippage. However, the knee brace and shoulder strap control had a similar level of variance when compared to the active Anklebot control. This probably results from the bimodal distribution of the brace control data. Frames of the smaller more positive mode of the knee brace with shoulder strap histogram, all frames with $x_{\text{deviation}}$ above -2mm, were grouped together. Frames in this group were from the toe-off region of the gait cycle. Higher $x_{\text{deviation}}$ at toe-off is probably a result of muscle flexion, primarily in the gastrocnemius, which was shown to change marker position up to 5mm. Future testing should consider countermeasures to minimize the effect of muscle flexion on centroid position estimation.

The exoskeleton and bungee configurations 1 and 5 did not do a better job of decreasing slippage than the shoulder strap according to Levene's test. Although Levene's test showed a similar variance to bungee configuration 5, the histogram seems very similar to the knee brace with shoulder strap histogram with a thinner distribution than the active Anklebot control. This suggests it should have a lower variance than that represented by the calculation. However, this cannot be proven with the current distribution.

Waist support configurations 2-4 significantly lowered variances, $p < 0.05$, compared to the shoulder strap support with active Anklebot. Two of these three trials had 3 bungees, trials 3 and 4, instead of 2 bungees as in the other configurations. This suggests that an apparatus capable of supporting greater loads does a better job of stabilizing Anklebot.

All prototype support methods other than waist support configuration 3 resulted from a decrease in marker separation after the calibration period. The brace shifted down on the leg after calibration in these trials. The shift downwards is most likely the result of the device being in an artificially high point during calibration. This could result from the subject pulling the knee brace up before beginning the trial or not walking around prior to the calibration period to settle the knee brace into a steady state position before calibrating.

All the waist support trials held the device in a significantly higher absolute position, ~2cm, than all of the controls. This suggests that the elastics are supporting more of the weight of the device than the shoulder strap. The exoskeleton, however, did not raise Anklebot's position on the leg at all. This probably results from the device supporting low amounts of Anklebot's weight or significant sagging of the exoskeleton under Anklebot's weight. The primary source of this unwanted flexibility came from the bearing just behind the heel. The tolerance between the bushing and the shaft was too high allowing movement on the order of centimeters along the tibial axis. If the exoskeleton prototype were pursued further, this component of the device is a key area prone to failure.

Only waist support configuration 3 had all the traits of a good stabilizing device. Anklebot shifted very little after calibration (low mean $x_{\text{deviation}}$) and a significantly lower variance than the active Anklebot control. It also held the knee brace at a much higher

position than the control, which suggests it does a very good job of supporting the weight of Anklebot. However, this configuration also restricted hip extension and flexion the most of all the waist support configurations. According to the subject, the force of the bungees was probably responsible for this restriction and that the greater loads in configuration 3 decreased comfort. A source of restriction is most likely the high spring constant of the elastics that applied significantly different supporting loads depending on elastic extension during hip flexion or extension. Elastics with lower spring constants producing the same supporting load would restrict gait less because they would apply a more even load over the hip's range of motion. Either getting shorter, weak elastics or stretching weak elastics over a larger distance would achieve the desired behavior.

If further experiments are run using this marker tracking protocol, imprecision in the current position tracking protocol should be quantified. This could be done by simultaneously tracking the same point with this method and another relatively precise position tracking protocol, such as flock of birds (LaScalza 142) The centroid tracking protocol's precision is roughly estimated at ~2mm from looking at the centroid position, gray square, on the markers. It is important to note that the position becomes less accurate as the markers move faster due to motion blur.

6 Conclusions

The waist support approach exhibits the greatest stabilizing behavior of the tested prototypes, significantly decreasing slippage from the active Anklebot control. This would be a significant improvement over the existing shoulder strap support system because it also makes the support system's structural loop much smaller. The exoskeleton failed to decrease slippage due to unwanted flexibility caused by play in the DP bearing. Both prototypes introduced some restriction of motion. The exoskeleton constrained movement at high angles of tibial rotation; however, there was minimal constraint during normal walking. The waist support had no restriction of range of motion below the knee but did restrict hip flexion and extension when more elastics were applied. This could be combated with weaker elastics. In conclusion, further pursuit of the waist support prototype is recommended.

Citations

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