A Disturbance Emulation Device for Stability and Recovery Testing

Blair J. Emanuel
Masters Candidate
Experimental Biomechatronics Laboratory
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213

Steven H. Collins
Associate Professor
Experimental Biomechatronics Laboratory
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213

In studies investigating stability and balance, there is a need for an automated perturbation device capable of applying consistent forces for stability studies. We propose a multi-axis system for disturbance emulation with a walking subject. The system is able to produce forces in multiple directions applied to several different locations on the subject. This allows for greater flexibility in testing and the ability to emulate various types of disturbances with a single test setup. The device is capable of producing force trajectories with magnitudes between 30-250N and durations greater than 150ms. The system was tested in both a static configuration and with a standing human subject. The rise time of the system was 35ms for static testing and 85ms for human testing. The normalized root mean square error of the measured trajectories was 33% for step responses and 3-6% for less abrupt shapes such as ramps or sinusoids. This system will help us to develop prostheses and exoskeletons that enhance the user's stability. It will also allow gait biomechanics researchers to quantify stability in a meaningful way under controlled conditions.

1 Introduction

The design and implementation of prosthetic and exoskeleton devices traditionally focuses on helping the human user walk normally on an even surface. However, as these devices become more sophisticated it will become necessary to shift to more dynamic walking situations. In real life, people are subjected to bumps, trips, and other disturbances while walking. By analyzing how people react and recover to these and other disturbances we can determine how to improve such devices and potentially prevent falls and other injuries.

Many studies investigating the stability and recovery of human subjects have been conducted previously. The majority of these studies focus on applying perturbations to subjects that are standing still, rather than walking. A variety of mechanisms are employed to create the perturbations including falling weights [2, 3], pulled ropes [1, 6], and rigid structures that push directly on the subject [4, 5, 7, 8]. These devices typically generate disturbances within a range of 50-250N and 150-300ms.

The main purpose of our proposed device is to give more flexibility in what types of stability experiments can be run. A large component of this is providing the ability to pull on the subject from multiple directions with a single setup. This would allow us to study a greater variety of balance responses without reconfiguring the device. It would also reduce the subject’s ability to predict and anticipate where the next perturbation will be applied. Two of the rigid structure devices [5, 8] provide this ability by having independent actuation systems for each axis. With our device, we propose a single actuation system capable of generating disturbances in two axis perpendicular axes and along different horizontal planes. This would greatly reduce the cost and complexity of the device while giving us the desired degrees of freedom.

Along with changing the direction of the perturbations, we wish to precisely control the profile of the applied force. The profile is defined by the peak applied force, the duration of the disturbance, and the general shape of
the force. For devices that use falling weights to generate disturbances [2, 3], these parameters are fixed or can be modified by changing the physical system. Systems with active actuation methods [1, 6] can potentially change these parameters programatically, which is the approach we would like to take. The disturbance force would be applied by a closed-loop controlled motor and the disturbance profile could be modified from within the software.

Finally, we wish to run tests on subjects that are walking on an instrumented treadmill. Therefore, the device should have a minimal impact on the subject's ability to walk. Rigid structures are often placed very close to the subject and cannot be installed around a treadmill [5, 8]. Those systems that use ropes or longer rigid structures to apply the disturbance [1, 4] avoid this issue by placing the main actuator far from the subject. This allows the device to be installed around a treadmill and to give the subject a free range of motion. Our device would be similar, with minimal hardware attaching to the subject. The main actuators would be placed behind the treadmill leaving the space clear for the subject to walk and move around.

Similar devices have also been used to improve stability, rather than to test it. A rope based system was used to relieve subjects of body weight during gait training [9]. The device was capable of applying horizontal and vertical forces, and was used in disturbance tests as well [10]. Another rope based system applies assistive forces on subjects with neurological impairments [11]. These stabilizing forces could easily be produced by a device designed to generate disturbances.

In order to assess our device, we would quantify its performance based on physical characteristics and dynamic responses. Previous devices use a range of metrics depending on the actuation system used to create the perturbations. With our device, we would consider the rise time of the system, the normalized root mean square error of the trajectory, and the impulse generated from a single disturbance. The rise time would measure of the system’s responsiveness to step-type profiles. The root mean square error would quantify the system’s ability to follow a desired trajectory. Differences between the desired and actual impulse would give an indication of how well the desired physical effect is produced. Combined, these metrics would allow us to evaluate our system and isolate areas in which the performance could be improved.

The purpose of this study is to design and validate a disturbance emulation device capable of being used for a range of experimental purposes. To create more varied disturbances, we have chosen an actuation method that can apply force in multiple directions with a single hardware configuration. The system should be capable of generating perturbations similar in magnitude, shape, and duration to those produced by previous devices. We wish to have precise control over these parameters and the ability easily switch between various types of disturbances. We have taken this approach such that our device will allow researchers to conduct stability experiments with more complex and diverse disturbance scenarios than previously possible. Additionally, the same setup could be used to apply assistive forces if desired and further expand the capabilities of a single experimental space.

2 Methods

We are developing an automated device for real-world disturbance emulation. Shown in Figure 1, the device consists of six ropes attached to a human subject at the waist and ankles. These ropes are pulled to produce the desired force profile on the subject. The profile is generated using closed-loop control based on tension measured in the ropes. The system was tested in configurations where the rope was rigidly attached to the devices frame and where it was attached to a standing human subject.

2.1 Physical System

The device consists of a rope connected to the subject at one end and a low-stiffness spring at the other. The ropes attach to a harness and straps at six points on the subjects body; the front, back, left, and right of the waist and the backs of both the ankles. The ropes are guided around the treadmill and back to the main actuation system using a series of pulleys. The opposite ends of the ropes pass through a novel clamping system mounted on a motorized platform. When a rope is clamped, the platform moves linearly to pull on that rope and apply a disturbance to the subject. The springs at the far ends of the ropes maintain a small amount of tension while allowing the human to move at the waist and legs. Each rope is instrumented such that the tension can be measured and used to control the disturbance.

The moving platform is made of quarter-inch aluminum plate custom machined to hold the clamping mechanisms (Figure 2). It is mounted on two pairs of linear bearings that slide along a hardened steel shaft. The shafts act as rails that constrain the linear motion of the moving platform. Limit switches on either end of the rails prevent the platform from moving too far and damaging the device.

![Fig. 2. Aluminum platform and clamping subsystems](image-url)
The platform is actuated by a rack and pinion mechanism mounted to its underside. The pinion is fastened directly to the shaft of the main motor (AKM52H-ACCNR-00, Kollmorgen). The motor itself is mounted underneath the rails to conserve space. A pair of steel rollers maintains contact between the gear teeth to prevent misalignment.

There are six independent clamping mechanisms evenly spaced along the width of the platform. Each mechanism consists of a modified spring-loaded boating cleat (70-07, Schaefer Marine, USA) and a small hobby servo (SG90, Hossen, China). The spring on one side of the cleat has been removed such that it is free-spinning. It is attached to the servo horn via a metal coil spring. The elasticity of the spring prevents the cleat from applying sharp forces to the servo when a rope is clamped. Without modification, the cleat only allows the rope to move in a single direction. By adding the servo actuation, the cleat can be either engaged or disengaged as needed. When disengaged, the rope can move freely in either direction without being affected by the cleat. If the cleat is engaged, it prevents motion in one direction while allowing it in the other. These two states are shown in Figure 3. The clamping systems are mounted such that when they are engaged the rope cannot slip while being pulled. The servo positions are controlled via an Arduino Uno (Arduino, USA).

The force in each rope is measured using a series pair of strain gages in a quarter-bridge configuration. The strain gages (SGT-2C/350-TY43, Omega, USA) are applied to either side of a thin aluminum plate to measure axial strain. By connecting this plate in line with the rope, tension is measured. For the purposes of this setup, it is assumed that there is no bending force acting on the plate and all forces are in line with the rope. The strain gages themselves are protected by custom fusion-deposition modeled covers. Only one amplifier is used for strain gage measurements, therefore a relay circuit is used to switch between bridges. This circuit is also directly controlled by the Arduino.

2.2 Control Code

The main control program is compiled to real time control hardware (DS1103, dSPACE Inc., USA) and is initially written in Simulink (Matlab, USA). A diagram of the entire software system is shown in Figure 5. Analog voltage measurements for the motor velocity, strain in the rope, and limit switch states are read at a frequency of five kilohertz. The motor velocity is used in the control scheme without conversion to other units. The strain measurement is initially low-pass filtered to remove any high frequency electrical noise. The filtered voltage is then converted to a force in Newtons based on prior calibrations for the circuit. The analog voltages from the limit switches are converted to binary states that are used to control the system behavior. All of the measurements are down sampled to a lower frequency of five hundred hertz before they are used by the control system.

The control system is a state machine that determines the behavior of the main motor, the clamping system, and the relays for strain measurement. There are specific states for clamping and releasing the chosen rope. The number of the rope is sent to the Arduino in binary using digital pins. The Arduino handles the positioning of the chosen servo
Fig. 4. Photograph of the force measurement device. Strain gages are applied to either side of a thin aluminum dog bone. A fusion-deposition modeled cover protects the strain gages and provides strain relief for the wires.

The iterative learning term, $\dot{X}_{\text{LRN}}$, is determined experimentally through repeated training of the system. For successive disturbances, the system modifies the learned term based on residual error in the force trajectory. The new term is fed forward to be used in the next pull. The filtered force error from previous pulls is added to the current learning term to update it based on the current pull (Equation 2). The $\mu$ value determines how much the force error influences the new term and is set to 0.7 in our experiments. Once the terms have been learned for a given disturbance trajectory they can be saved and used at a later time to avoid retraining the system.

$$\dot{X}_{\text{LRN},\text{new}} = \dot{X}_{\text{LRN},\text{current}} - \mu \text{filtered}$$  (2)

2.3 Experimental Methods

We performed tests of the system’s overall ability to produce desired force profiles, its ability to switch between ropes when pulling, and its ability to accurately apply disturbances to human subjects. The first two tests were run with a static configuration. Rather than attaching to a subject, the ends of the ropes were connected to the frame of the device. For testing with humans, the rope was attached to a harness at their waists.

To demonstrate the controllability of the device, we trained the system on a variety of force trajectories. The shapes used were a step response, a ramp, a sinusoid, a double sinusoid, and a Gaussian curve. The shape of the profile could be selected within the user interface, without having to change any part of the underlying program. All trajectories had the same duration and peak magnitude of 300ms and 150N, respectively. They were run using a static configuration as described above. The normalized root mean square errors for these trajectories were analyzed to determine how well they matched the desired shapes.

An important aspect of the device is its ability to disturb a given rope without affecting the other ropes in the system. This was tested by instrumenting two ropes to simultaneously measure their tensions. An additional signal amplifier was used to take these measurements. The ends of the ropes were statically connected to the frame of the device. Each rope was pulled sequentially and followed a step response of 150N for 300ms. The rise times of the two step responses were calculated to give a measure of the responsiveness of the system. The normalized mean square error and impulses were examined as well. Additionally, the force on the undisturbed rope was measured to evaluate the system’s rope switching capabilities.

The system was also tested with a subject to show that the desired force profiles could be achieved with a human in the loop. The active rope was attached to the front of the subject’s waist and the subject stood facing the device. Step response force profiles of 150N and 300ms were applied. Once again, the rise times, mean square error, and impulses were measured.

$$\dot{X}_{\text{motor,des}} = -K_p \text{error} - K_d \dot{X}_{\text{motor,actual}} + \dot{X}_{\text{LRN}}$$  (1)

The control output is the commanded velocity of the main motor which drives the motion of the platform. The proportional term uses the error between the desired rope tension and the actual rope tension. Instead of the derivative of the force measurements, the system uses the actual motor velocity as returned by the motor controller. This has the same effect as a traditional derivative term by smoothing the overall motion of the platform.
Fig. 6. Measurements from different force profiles. All profiles have a peak force of 150N and a duration of 300ms.

3 Results

We have constructed a prototype disturbance emulator and completed benchtop testing. The system can reliably engage, displace, and release one of the six disturber ropes without affecting the surrounding ropes. The tension in the rope closely follows the desired force trajectories for all shapes.

The results from testing various force trajectory shapes are plotted in Figure 6. The device was able to produce disturbances following all the desired trajectories. From top to bottom, the normalized root mean square errors of the profiles were 35.14%, 3.43%, 4.21%, 5.05%, and 2.76%. All calculations are based on an average pull calculated from five trained pulls.

A demonstration of the system’s ability to pull on ropes individually is shown in Figure 7. The different colors signify the two different ropes that were measured. For this test, the average of ten trained disturbances was evaluated. The normalized root mean square error of the two disturbances are 25.22% and 15.21%. The percent difference in impulses of the two pulls are 7.103% and 4.56% and the rise times are 58.6ms and 34.8ms. The peak forces in the undisturbed ropes were both less than 8N.

The system had similar results when it was tested with a standing human subject (Figure 8). The normalized root mean square error and impulse difference was 33.09% and 9.26%, respectively. The rise time for the average step response was 85.4ms.

Fig. 7. Force profiles for two independent ropes during static testing. Both desired profiles had a magnitude of 150N and a duration of 300ms. The red and blue lines represent two different ropes that are pulled a specified time apart.

Fig. 8. Step response force profile for a single rope disturbing a standing human subject. The desired pull had a magnitude of 150N and a duration of 300ms. Ten trials were run and the resulting profiles were averaged.

4 Discussion

Our purpose was to create a device capable of applying numerous types of disturbances in different directions on a human subject. It has demonstrated an ability to do so in benchtop testing. The device will be useful for evaluating the stability and balance of walking subjects. It will aid us in assessing the effectiveness of various recovery strategies for both our exoskeleton and prosthetic devices.

Although the overall behavior of our device is similar to those used in previous studies, our unique actuation mechanism gives us more flexibility in testing. The multi-rope design allows disturbances to be generated in a variety of directions as needed. Some of the more rigid devices [5, 8] have this capability as well. However, because of the use of ropes, it is easy to change the attachment points of our device and more tightly control where disturbances are
applied to the subject. It is also possible to change the profile of the disturbances directly from the software interface.

The weight-driven devices [2, 3] can change the magnitude and duration of the disturbances by changing the height and mass of the weight. By using active control, our device allows the experimenter to make these same changes without modifying the physical system. It is likely this is possible with other motor-driven devices [1, 6] although they have not highlighted this ability.

The range of possible peak forces and durations is based on those used by earlier devices. Our device can therefore produce disturbances that are equivalent or comparable to most disturbances that previous devices could generate. In general, our system has the ability to emulate a wide range of behaviors with a single piece of hardware. This will permit us to run a variety of experiments in the same space even if the perturbations being investigated are vastly different.

One major limitation of the device’s design is that it can only pull on a single rope at a time. For our experimental needs this is sufficient and the system can switch between ropes rapidly if needed. However, if the desired direction is not along one of the cardinal directions already in place the system will need to be physically reconfigured. The ropes can be easily attached to various points on the body and the pulley routing system can be built to accommodate new rope directions as necessary. The current test setup also uses shorter ropes than the final system. The additional rope length will add more elasticity to the system and affect the overall dynamics. A possible solution would be to use a rigid link for long distance spans rather than using semi-elastic rope for the entire distance.

Now that benchtop testing of the device is complete, we will begin running experiments on walking humans. Initially, we wish to confirm that we can reliably generate the desired force trajectories on a moving subject. Once the device’s capabilities have been established, we will begin testing in conjunction with our exoskeleton and prosthetic devices. Our disturbance emulation device will be used to systematically perturb the subject and allow us to better assess their balance and response behaviors. We can use the results from such experiments to create controllers that improve these behaviors and help restore the subject’s stability.

5 Conclusion

We have demonstrated that our system can successfully engage, pull, and release selected ropes with a desired force trajectory. It does so both in a static testing configuration and when the disturbance is applied to a standing human subject. This device will make it easier to run a variety of stability and balance experiments with a single setup. It will also allow for more varied behavior within a single experimental trial. We hope it will allow us to better explore human balance responses and inform future controller designs for exoskeletons and prosthetic devices.

References