Gait Emulator for Evaluation of Ankle–Foot Prostheses Capable of Turning[1]

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1 Background

One of the challenges in the development of prostheses is the testing and tuning of the mechanism before testing with human subjects. It is a common practice in the industry to use testing platforms to tests new products for different properties such as strength and fatigue; however, few platforms have been developed for testing and tuning of ankle–foot prosthesis. Before testing the lower extremity prostheses with human subjects, the designers need to assure that the device would perform as designed, otherwise it may result in injury. Another issue that may arise is the lack of repeatability during evaluation experiments with human subjects. Humans have a remarkable ability to adapt to new environments; hence, studying the effects of any tuning in the prosthesis performance may not be conclusive, as it may not always be clear if the outcomes are due to the changes in the prosthesis, or due to the adaptation by the amputees.

Richter et al. reported a testing apparatus to evaluate the lower extremity prostheses in the sagittal plane [1]. Sagittal plane testing of leg-prostheses meets the requirements for testing the currently available powered ankle–foot prostheses, which control the ankle only in the sagittal plane and focus on straight walking. However, depending on the activity, turning steps may account for up to 50% of the steps [2]. Turning steps require modulation of the torques and angular displacements of the ankle–foot mechanisms in both the sagittal and frontal planes resulting in increased lateral and propulsive impulses when compared to straight walking [3].

The need of a device to help in testing and development of ankle–foot prostheses with two DOFs (degrees of freedom) motivated the present work. A gait emulator that can be used with both standard and circular treadmills was developed (Fig. 1), allowing testing and tuning of different types of ankle–foot prosthesis, including active and passive, and working as an intermediate step between design and human trials. The gait emulator was used together with a custom-made circular treadmill to develop and tune an ankle–foot prosthesis with two DOFs in the frontal and sagittal planes.

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2 Methods

The gait emulator (Figs. 1 and 2) is designed to work with both the circular treadmill as well as regular gym treadmills. In Figs. 1 and 2, the gait emulator is presented with a circular treadmill and a passive prosthesis (A). Unlike a regular treadmill, where the user walks in a straight line, in a circular treadmill the user needs to always be turning to stay on top of the treadmill; which makes it suitable for testing and tuning ankle–foot prosthesis for turning. The circular treadmill is composed of a wooden disk with a 1 m radius (B). On the outside lower edge of the disk, eight coaster wheels (C) are connected for weight-bearing. Also, a heavy-duty turn table (not visible) is mounted in the center of the disk for both weight-bearing and constraining the disk from sliding on the horizontal plane. A 343 W brushed motor (Banebots First CIM) and planetary gearhead with a 64:1 gear ratio (D) provide power for the rotation of the disk using a belt system (J) with a reduction ratio of 5.3:1 resulting in a total 339:1 reduction from the DC motor to the circular treadmill. This results in a maximum walking speed of 1.63 m/s, which is sufficient considering the average preferred human walking speeds for young adults is

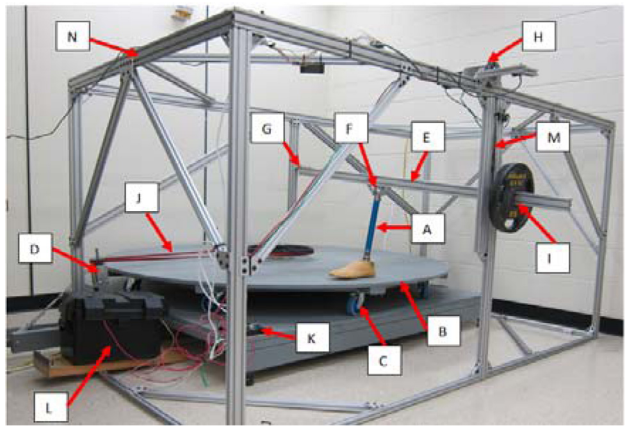

Fig. 1 Gait emulator and circular treadmill and its main components

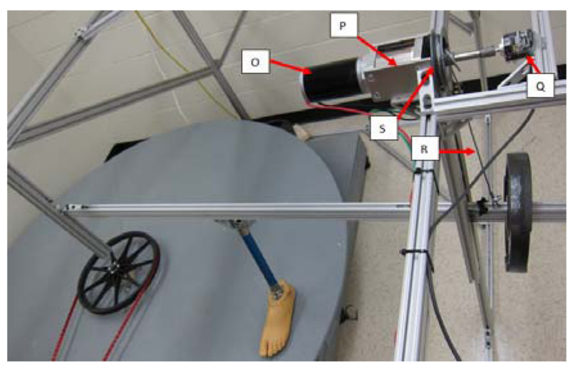

Fig. 2 Top view of the gait emulator and circular treadmill

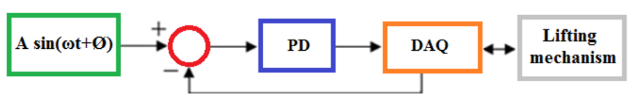

Fig. 3 Block diagram of the lifting mechanism controller. The input is a sine wave with amplitude of A degrees of the cable drum rotation, frequency of steps ω, and phase shift Ø to synchronize the gait emulator to the motion of the ankle–foot prostheses.

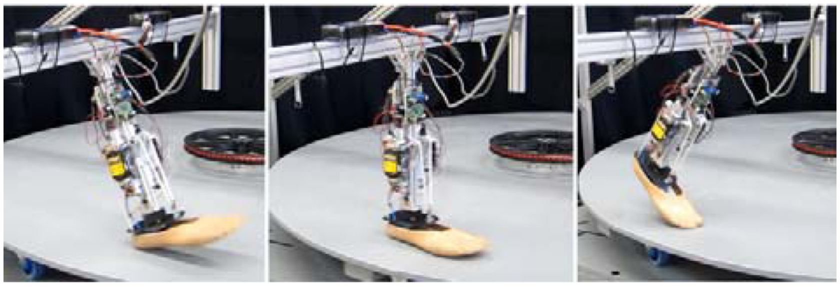

Fig. 4 Gait emulator and a prosthetic ankle–foot robot with two controllable DOFs in both the frontal and sagittal planes at different states of the gait. (*a*) Heel-strike, (*b*) foot-flat, and (*c*) push-off.

1.30 ± 0.1 m/s [4]. The speed of the treadmill disk is controlled using an open loop speed controller and powered by a motor controller (K) (RoboteQ LDC 2250C) and the power is supplied by a 12 V deep cycle battery (L).

The prosthetic ankle–foot (A) is connected to a horizontal bar (E) by a universal joint (F), which acts as a passive knee. At one end, the bar (E) is connected to a pivot (G) and at the other end to a cable (R). The cable itself is connected to a 343 W brushed motor (O) (Banebots First CIM) and gear box with a 36:1 gear ratio (P). A cable drum with 10 cm diameter (S) is connected to the gearbox (P), which by winding the cable (R) can raise and lower the bar and the prosthesis. The motors for the lifting mechanism and the treadmill are controlled by the same motor controller (K), which is capable of controlling two DC motors. The bar (E) is also capable of bearing loads (I) that is supported by the prosthetic leg when the weight is lowered during the stance or by the lifting mechanism when the leg is raised during the swing. The bar is constrained to only slide up and down using a sliding mechanism (M). The amount of weight can be modified to simulate different users' weight. The prosthetic leg, bar, motor and gear box, and weights are attached to an aluminum frame (N) that is not coupled to the treadmill except through the foot at the time of the stance when it contacts the wooden disk. The circular treadmill can be easily replaced by a standard gym treadmill as it is not directly connected to the gait emulator.

The lifting mechanism uses a proportional-derivative (PD) controller (Fig. 3) with feedback from a quadrature encoder (Q). The PD controller input is a sine wave with the same frequency as the gait. The sine wave has an amplitude of A degrees, which corresponds to the cable drum rotation, frequency of steps (ω), and phase shift Ø to synchronize the gait emulator to the motion of powered ankle–foot prostheses. These values are dependent on the prosthetic ankle–foot tuning, amount of weight being used, and the position of the prosthesis with respect to the frame and treadmill. The lifting mechanism is capable of lifting 118 kg at 10.6 m/s. However, the weight supported by the prosthetic leg is higher due to leverage, resulting on the weight supported by the prosthesis to be a function of the position of the pylon with respect to the beam (E) and the amount of weight installed on the mechanism. Using the presented circular treadmill, which was designed to emulate gait during turning, the radius of the turn of each step can be increased or decreased by sliding the frame (N), so the foot is closer to or farther away from the center of the treadmill. Currently, the prosthesis pylon angle is not controlled, and the "knee" joint is a passive one DOF joint resulting in a free swing forward phase. The versatile design of the gait emulator allows to use active knees to control the swing phase speed or to be modified to be used to test and tune prosthetic legs containing both hip and knee with either passive or active joints.

3 Results

The gait emulator and circular treadmill were successful at mimicking gait during turning using both passive and active prostheses. Figure 4 shows a prototype ankle–foot prosthesis with two controllable DOF in both the frontal and sagittal planes at different states of the gait while walking on the circular treadmill using the gait emulator with a 25 kg load. The input sine wave was set with amplitude of the rotations of the cable drum to 100 deg which corresponds to a vertical displacement of 8.9 cm of the knee joint, and the gait frequency was set to 48 steps per minute. The active ankle–foot prosthesis shown in Fig. 3 uses two PD controllers to control dorsiflexion–plantarflexion and inversion–eversion rotations. The gait emulator was used to tune the prosthesis PD controllers, which used prerecorded trajectories of the human ankle to adjust the neutral position of the ankle and position feedback from the prosthesis' quadrature encoders to estimate the appropriate motor inputs.

4 Interpretation

The gait emulator and treadmill provided a platform for testing ankle–foot prostheses, which allows for consistent and repeatable measurements and tuning. In the presented work, the gait emulator and circular treadmill were used to tune the PD controllers of a powered ankle–foot prosthesis as shown in Fig. 4. Future research will include a motion capture camera system to measure the kinematics of the prosthesis during the gait. Also, the camera system will be used to measure the human gait while walking on the treadmill for comparison. The treadmill will also have modular terrain profile elements, which can be added to simulate off-camber turn, ascending, descending, and traversing the slopes. These terrain profile elements will be used to tune the prostheses' controller for disturbance rejection and surface profile adaptation.

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