

Design and Validation of an Instrumented Uneven Terrain Treadmill

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Abstract. Studying human and animal locomotion on an uneven terrain can be beneficial to basic science and applied studies for clinical and robotic applications. Traditional biomechanical analysis of human locomotion has often been limited to laboratory environments with flat, smooth runways and treadmills. The authors modified a regular exercise treadmill by attaching wooden blocks to the treadmill belt to yield an uneven locomotion surface. To ensure that these treadmill modifications facilitated biomechanical measurements, the authors compared ground reaction force data collected while a subject ran on the modified instrumented treadmill with a smooth surface with data collected using a conventional instrumented treadmill. Comparisons showed only minor differences. These results suggest that adding an uneven surface to a modified treadmill is a viable option for studying human or animal locomotion on an uneven terrain. Other types of surfaces (eg, compliant blocks) could be affixed in a similar manner for studies on other types of locomotion surfaces.

Keywords: walking, running, ground reaction forces, locomotion

Understanding human and animal locomotion on different surfaces could improve clinical rehabilitation and the design of prosthetic devices. Currently, studies focusing on locomotion on uneven terrain are conducted either on short, uneven walkways¹⁻⁸ or in natural environments, such as grass, sand, snow, and other terrain.⁹⁻¹² However, outdoor studies preclude the collection of data that require externally powered, heavy, or sensitive equipment. As a result, it is often not possible to obtain ground reaction force (GRF), kinematic, or muscle electromyographic data. Conversely, conventional laboratory experimental setups limit the range of surfaces over which data can be collected. This makes it difficult to obtain kinetic and kinematic information over more than a few steps or to quantify biomechanical and energetic adaptations over time. To bypass the limited range of surfaces, some experiments have modified existing treadmills either by attaching discrete obstacles or even by creating a continuous balance beam using a set of narrow blocks.^{13,14} However, discrete perturbations on a treadmill do not allow for measurements of steady-state dynamics and are not suitable for measuring biomechanical adaptations or energetic consequences of continuous locomotion on an uneven terrain. For these reasons, we sought to construct an uneven terrain treadmill that would allow for experimental control of terrain variation and trial duration.

To this end, we modified a commercially available exercise treadmill to allow for attachment of wooden blocks to the treadmill belt. The modified

instrumented treadmill could then be used to collect biomechanical, metabolic, and other gait data during continuous walking or running on an uneven surface in a laboratory setting. Here, we describe our methodology for creating such a treadmill. We also verified that our modified treadmill, with the uneven surface removed, produced similar biomechanical measurements as a conventional instrumented treadmill with a smooth and flat belt.

Methods

We modified a commercially available exercise treadmill (Trackmaster TMX22, JAS Fitness Systems, Dallas, TX) to facilitate attachment of a separate, uneven surface. First, we separated the motor and electronics box located at the front base of the treadmill and reattached it further forward on the treadmill frame. This created an approximately 10-cm gap between the front treadmill roller and the motor box, so we replaced the original drive belt with one of the appropriate length. These modifications created room for obstacles placed on the treadmill belt to curve around the treadmill rollers without being obstructed by the motor box. To create clearance below the treadmill, we placed the treadmill atop 2 custom-made steel support beams (Figure 1F). Only the frame of the treadmill rested, unfastened, on the support beams, with the treadmill belt unobstructed. Each support beam rested directly on an in-ground force platform. As a result, all GRFs were registered by the 2 force platforms. To ensure the subjects' safety, a custom-made platform onto which subjects could step off surrounded the raised treadmill.

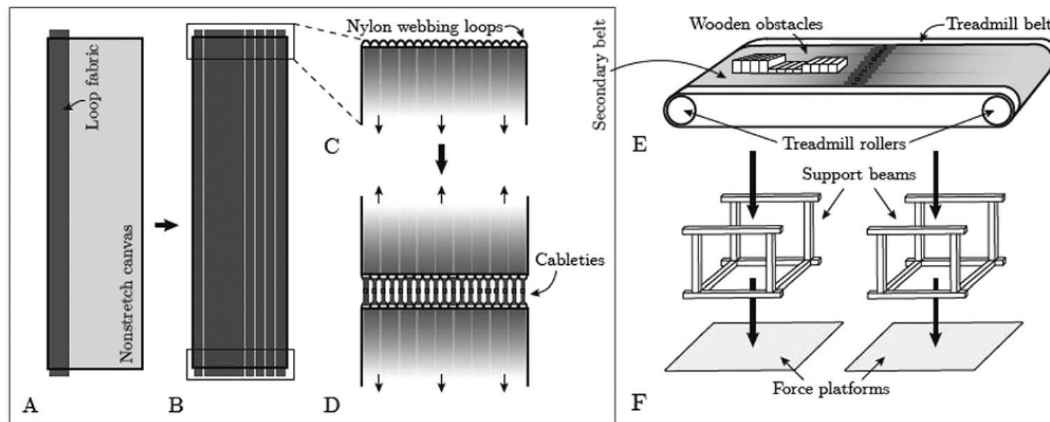


Figure 1. Design of the secondary, uneven terrain belt. (A) Thick nonstretch fabric is used as the base material. (B) Loop fabric is sewn directly onto the canvas to cover it completely. (C) Nylon webbing loops are added at each end of the belt. (D) Once the secondary belt is placed around the treadmill rollers, the 2 ends are secured together with cable ties that go through the loops at the end. (E) The secondary belt rests on top of the primary treadmill belt, and wooden obstacles are added as desired using hook-and-loop fabric. (F) The treadmill is then placed atop 2 support beams that rest directly on the 2 force platforms below.

We designed the uneven surface as a secondary belt that could be placed atop the original treadmill belt (Figure 1A-1D). We sewed the secondary belt out of thick nonstretch canvas to match the width and length of the original treadmill belt. At both ends of the belt, we attached 16 loops made out of 1.27-cm-wide durable nylon webbing. The 2 ends of the secondary belt could then be connected to each other with cable ties after wrapping the secondary belt around the treadmill rollers and on top of the primary belt. The cable ties allowed us to remove and attach the surface with ease and offered the ability to tension the secondary belt. Operating the treadmill for several minutes without a subject, retightening the cable ties, and repeating as necessary helped us ensure that the secondary belt did not slip during testing. To attach blocks to the secondary belt, we sewed 5-cm-wide strips of industrial-grade loop fabric (Velcro, Manchester, NH) along the entire surface of the secondary belt. These strands extended past the end of the secondary belt by 10 cm to cover the connecting cable ties. This created a continuous loop-fabric surface.

We used wooden obstacles of different heights to create the uneven surface. 15 Blocks were custom-made from sugar pine and were 2.54 cm wide, 15.2 cm long, and of 3 different heights (1.27, 2.54, and 3.81 cm). We glued industrial-grade hook fabric (Velcro) to the bottom of each block. This allowed us to attach and remove obstacles from the loop fabric on the secondary belt. Each block was arranged lengthwise across the belt, allowing the short side of the obstacle to curve around the

treadmill rollers. We arranged blocks in 3 columns along the length of the belt, in 15.2 x 15.2 cm stepping areas consisting of 6 blocks of the same height. These areas alternated by height in each column, with the ordering offset by one. This created a patterned uneven surface that, due to the column offset and relatively short stepping areas, appeared random during walking (Figure 2).¹⁶

To test the validity of our setup, we tested 1 representative male subject running on a conventional instrumented treadmill (Bertec, Worthington, OH) and on the modified instrumented treadmill without the secondary uneven surface belt. We placed the modified treadmill and support beams on top of 2 in-ground force platforms (sample rate: 1000 Hz; model OR6-7-1000; AMTI, Watertown, MA) 0.5 m apart. On each treadmill, the subject ran for 2 minutes at a speed of 2.3 m/s, matching our previously used running speed on an uneven terrain.¹⁶

We collected GRFs from both setups. For trials collected on the modified treadmill, we transformed all GRFs and moments into the treadmill surface coordinate system, because the walking surface was significantly higher than the force platforms. We did this to ensure accurate center of pressure calculations. Such transformations are theoretically not necessary for calculating inverse dynamics, as long as all calculations are done along the force vector. However, some commercially available software for calculating inverse dynamics may require the GRF origin to be within a certain distance of the foot segment. To evaluate the power spectrum of the force data, we performed

fast Fourier transform analyses on the raw vertical and fore-aft GRFs. To reduce mechanical artifacts and the high noise sensitivity of the force data, we low-pass filtered all data at 20 Hz (fourth-order Butterworth filter, zero lag). We then normalized all force data to the subject's weight, calculated by averaging the filtered vertical GRF during stance for all steps in the trial. This means that forces from the 2 setups were normalized to 2 different values.

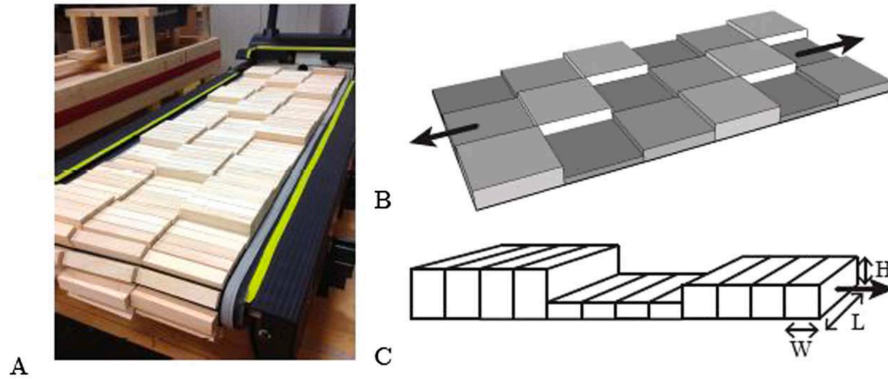


Figure 2. Uneven terrain pattern and close-up. (A) Photograph of the uneven surface attached to the treadmill. (B) Schematic of the uneven surface, with stepping areas of 3 different heights (arrows indicate the treadmill's long axis). (C) Close-up of the blocks comprising the stepping areas. Dimensions: H, 1.27 cm; L, 15.2 cm; W, 2.54 cm.

Results

GRFs in all directions were similar for the 2 treadmill setups (Figure 3A). Mean vertical forces, used as estimates of the subject's weight, were within 2% of each other (mean [SD]: 767 [35.5] N and 779 [26.0] N for the conventional and modified treadmills, respectively). Similarly, mean peak vertical GRFs on the conventional and modified treadmills differed by less than 1% (mean [SD]: 1.71 [0.04] and 1.70 [0.04] in units of body weight, for conventional and modified treadmills, respectively). Vertical force variability was slightly larger for the conventional treadmill than for the modified treadmill (mean [SD]: 0.081 [0.04] and 0.077 [0.03] in units of body weight, for conventional and modified treadmills, respectively). The fore-aft and mediolateral GRF profiles from the modified treadmill were similar to those recorded on the conventional treadmill, although with higher step-to-step variability.

The advantages and disadvantages of lowering the filter cutoff frequency to reduce this noise (Figure 3B) are addressed in the Discussion section.

Power spectrum analyses of the raw vertical GRFs on the 2 treadmills, analyzed over the full trial, showed differences in frequencies higher than 25 Hz (Figure 4). At lower frequencies, power

Then, we parsed the GRF data into individual steps, more than 300 on each treadmill, normalized to stance duration, and averaged over all steps. We defined stance using the onset and end of the vertical GRF, indicating heel strike and toe off, respectively. To calculate force variability for each condition, we found the SD of the normalized GRF data over all steps, calculated at each time point.

distributions were similar. By contrast, the power spectrum of the raw fore-aft forces showed a significant frequency component in the modified treadmill data at a lower, 10-Hz frequency; however, this frequency component was not present in the data from the conventional treadmill (Figure 4).

Discussion

Measured GRFs showed small differences between mean and peak values when running on the modified and conventional treadmills and were likely within natural gait variability values.¹⁷ Discrepancies in GRF data could be due to differences in surface stiffness, and past research indicates that humans adjust their leg stiffness while running to maintain similar GRF profiles in response to variations in surface stiffness.^{18,19} Here, we presumed any differences in surface stiffness between the 2 treadmills were minor. However, such differences could introduce error to calculations relying on GRF data, such as inverse dynamics analyses.

Fore-aft forces obtained from the modified treadmill showed a clear sympathetic vibration around 10 Hz (Figure 4). This is consistent with the power spectrum of previously recorded GRFs while running on the uneven terrain treadmill. This implies

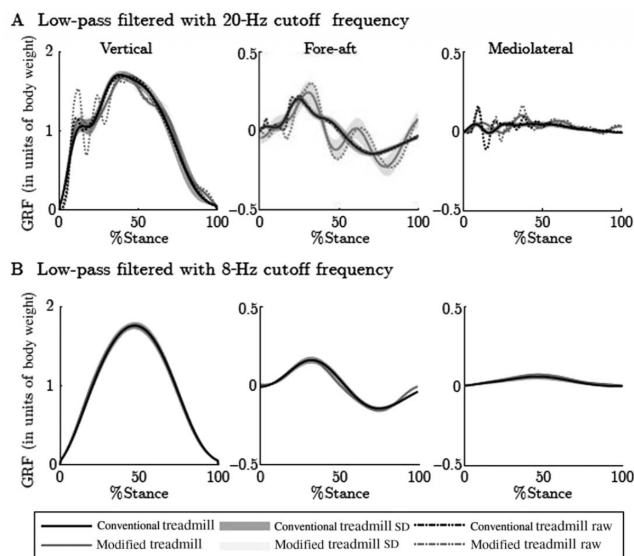


Figure 3. Comparison of GRFs during level-ground running on conventional and modified treadmills. (A) Vertical, fore-aft, and mediolateral GRFs for the 2 running conditions, low-pass filtered at 20 Hz. Raw data are indicated by dashed lines. Shaded regions indicate SDs of the mean, or force variability. (B) Force profiles in all 3 directions, low-pass filtered at 8 Hz. GRF indicates ground reaction force.

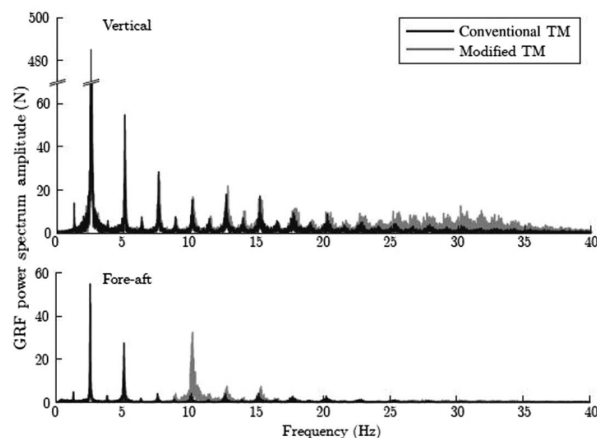


Figure 4. Power spectrum analysis of vertical and fore-aft GRFs during level-ground running on conventional and modified treadmills. Major differences between the 2 treadmill setups are primarily seen at higher frequencies and at around 10 Hz in the fore-aft direction. GRF indicates ground reaction force.

that any mechanical vibrations are likely due to the natural-frequency dynamics of the modified treadmill and are not significantly affected by the addition of the secondary belt with blocks. One option for addressing this noise is to use a notch filter to remove dynamics specific to a particular treadmill setup. However, we found that a low-pass filter with a cutoff frequency of 8 Hz effectively mitigates the effects of noise in GRFs (Figure 3B) and results in a high correlation between the force

profiles collected from the 2 treadmill setups ($R > .98$). In addition, although a low cutoff frequency visibly removes information from the force profiles, there is a benefit in filtering kinetic and kinematic data at the same cutoff frequency,²⁰ with 8 Hz being a commonly used cutoff for filtering kinematic data. If filtering is the same for all running conditions, such a low cutoff frequency is not likely to affect comparisons across different terrains.

Although data obtained using the modified and conventional treadmills are highly comparable while running on an even surface, adding an uneven surface to the modified treadmill could introduce small errors into center of pressure calculations. As mentioned previously, we chose to transform the recorded forces and moments into the treadmill coordinate system. For uneven terrain conditions, we propose to define the treadmill coordinate system at the lowest point of the terrain surface. This means that, due to surface height variability, actual points of foot contact could be higher than the calculated center of pressure (eg, when the foot is placed across blocks of different heights). We can calculate the maximum error in the center of pressure position this would cause by projecting the force vector from the lowest point of the treadmill surface (our defined coordinate system) onto the highest point on the terrain (where the foot may actually be in contact with the ground). Given a terrain height variability of 2.54 cm, and assuming a maximum force angle of 30 degrees from vertical in the sagittal plane, the maximum error would be less than 1.5 cm in the fore-aft direction, and generally would be substantially smaller. During both walking and running, the error in the coronal plane would be even smaller. Inverse dynamics calculations should not be significantly affected by the addition of the uneven surface, although increased variability in all measurements relying on the center of pressure location is possible.

In conclusion, the treadmill modifications and uneven surface designs presented here could be useful in many types of biomechanical studies on human locomotion. Other types of terrain elements, such as compliant or viscous blocks, can be attached to the treadmill belt to study how different types of terrain influence human locomotion biomechanics and energetics. Experimenting with different types of terrain would allow for studies of human movement across more diverse surfaces.

Acknowledgments

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