

special communication

Force treadmill for measuring vertical and horizontal ground reaction forces

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Kram, Rodger, Timothy M. Griffin, J. Maxwell Donelan, and Young Hui Chang. Force treadmill for measuring vertical and horizontal ground reaction forces. *J. Appl. Physiol.* 85(2): 764–769, 1998.—We constructed a force treadmill to measure the vertical, horizontal and lateral components of the ground-reaction forces (F_z , F_y , F_x , respectively) and the ground-reaction force moments (M_z , M_y , M_x), respectively exerted by walking and running humans. The chassis of a custom-built, lightweight (90 kg), mechanically stiff treadmill was supported along its length by a large commercial force platform. The natural frequencies of vibration were >178 Hz for F_z and >87 Hz for F_y , i.e., well above the signal content of these ground-reaction forces. Mechanical tests and comparisons with data obtained from a force platform runway indicated that the force treadmill recorded F_z , F_y , M_x and M_y ground-reaction forces and moments accurately. Although the lowest natural frequency of vibration was 88 Hz for F_x , the signal-to-noise ratios for F_x and M_z were unacceptable. This device greatly decreases the time and laboratory space required for locomotion experiments and clinical evaluations. The modular design allows for independent use of both treadmill and force platform.

biomechanics; locomotion; force platform

OUR GOAL was to construct an improved force treadmill (FTM) for measuring the forces and moments exerted on the ground by walking and running humans. Previous force-measuring treadmill devices have been shown to reduce substantially data-collection time for locomotion experiments, to allow for feedback to subjects and/or patients, and to enable experiments to be conducted that are not otherwise possible (9, 11–13, 16). However, previous designs could satisfactorily measure only the vertical force component. We sought to build a FTM that can record all three components of the ground-reaction force: vertical (F_z), horizontal (F_y), and lateral (F_x), as well as the moments (M_z , M_y , and M_x). These measurements are necessary for measuring the mechanical work performed on the center of mass, for determining the point of force application, and for calculating joint moments.

Various combinations of force platforms or force transducers with treadmills have been constructed in the past, but each of the designs had limitations. Several laboratories have mounted a force platform inside a treadmill (15, 17, 19) or built a treadmill around a ground-mounted force platform (8, 10). These devices could record the vertical ground-reaction force

and the moments around the lateral and anterior-posterior axes with excellent fidelity, but they could not measure F_y , F_x , or M_z . Other investigators have mounted a treadmill on top of multiple force sensors (4, 14, 18, 20, 22). Although these designs could measure F_y in addition to F_z , M_x , and M_y , they have done so with unsatisfactory fidelity. Frequency-response characteristics and signal-to-noise ratios were beyond limits normally considered acceptable. For example, the natural frequencies of F_z for all these designs have all been <45 Hz. These previous attempts were hampered by three factors: large treadmill mass, inadequate overall stiffness, and vibrations induced by the motor or rollers. We have developed a FTM that is a hybrid of these two basic designs.

METHODS

A 1-in. (2.5 cm)-thick aluminum plate was firmly affixed to the laboratory floor with epoxy glue, bolts, and concrete anchors. We mounted a large 71 × 24 in. (180 × 60 cm) commercial strain-gauged multicomponent force platform [model ZBP-7124-6-4000; Advanced Mechanical Technology (AMTI), Watertown, MA] to the aluminum plate. The treadmill chassis was bolted to threaded metal inserts in the top surface of the force platform. The main chassis of the treadmill was built from 4-in. (10-cm) 6061 aluminum I-beams that were connected by eight cross-members made of 2-in. (5-cm) aluminum channel. The bed of the treadmill was made of 0.25-in. (6-mm)-thick 6061 aluminum plate with a thin Teflon sheet to reduce belt-bed friction.

The rollers were custom-made on a lathe from a single piece of steel to achieve excellent balance and thus to minimize induced vibrations (F. & G. Williams Machine and Tool, Hatboro, PA). The rollers had a diameter of 3 in. (8 cm) and a face width of 14 in. (35 cm). The rollers had a slight taper crown for better belt tracking. A custom-made lead screw device allowed for tensioning of the belt by moving the nondrive roller along the horizontal long axis of the chassis. A 2-hp (1,500-W) variable-speed alternating-current electric motor (Leeson Electric, Grafton, WI) was mounted on the main chassis. A timing pulley on the motor shaft was connected to a larger pulley on the drive roller by means of a standard rubber timing belt. With the use of two different timing-pulley combinations, treadmill speeds of 0.5–7.0 m/s were easily achieved.

In addition, a flywheel mounted on the drive roller shaft helped to maintain a nearly constant belt speed during operation. We have found that a very large timing pulley works adequately as a flywheel, although a custom-machined balanced flywheel would be preferable. For safety, the drive pulleys and flywheel were covered with a plywood box that did not touch any of the drive parts or the force platform. For safety in mounting and dismounting, handrails were at-

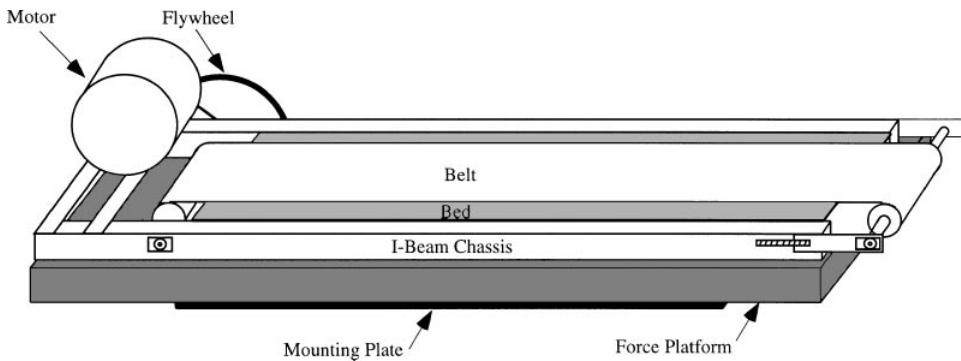


Fig. 1. Schematic view of force-treadmill (FTM) design. Handrails and gearbox cover are omitted from this drawing.

tached to the surrounding laboratory floor. We monitored the speed with a tachometer that detected the revolution rate of the drive roller. The overall design is shown in Fig. 1.

It is important to recognize that the entire treadmill (motor, drive pulleys, rollers, chassis, and so forth) was supported by the force platform. This was an essential design feature. If the motor were not mounted on the force platform, we would have had to measure the forces and torques imparted by the motor on the force platform. The chassis was supported in a distributed manner along its entire length. Some previous FTM designs have been "simply supported" (3) at four points by force transducers; thus they were much less stiff, particularly in the vertical direction. The total mass of our treadmill was 90 kg. A rough breakdown of the major components of this mass was as follows (in kg): I-beam chassis, 20; treadmill bed, 3; motor, 17; flywheel, 19; and two rollers, 14 each. High-frequency response is desirable in any force-transducing system. The natural frequency of vibration for any object can be increased by decreasing the mass. The most obvious treadmill components that could be lightened are the flywheel and the rollers. An ideal flywheel would have its mass concentrated on the rim to maximize the inertia-to-mass ratio. Rollers made of aluminum rather than steel would save nearly 20 kg. Titanium components would provide further mass reduction but at considerably greater expense. One advantage of our design was that the treadmill could be readily removed from the force platform, so that both pieces of equipment could be used independently for other experiments.

RESULTS

We performed a battery of static and dynamic tests to evaluate the fidelity of the FTM.

Linearity. We found it convenient to "tare" the force platform in the vertical direction; that is, we balanced the amplifier bridge circuit to give zero voltage output when the treadmill was mounted on the force platform. To ensure that this did not cause any distortion of the signal, we performed a static-force calibration with the treadmill mounted on the force platform. When we applied known loads, the output voltage response was linear to within 0.2% over a range of applied forces up to 2,300 N ($R^2 > 0.99$).

Point of force application. To verify that the position of force application did not affect the vertical-force output, we applied the same static load (700 N) at different locations. As expected from the manufacturer's specifications, the recorded voltage output from the amplifiers varied <0.7% from the mean, regardless of the location of force application. To determine the accuracy with which we could locate the point of force

application, we placed a known static load at various known positions along the length and width of the treadmill (6). The position of static-force application could be resolved to within 0.5 cm for the y -axis and 0.6 cm along the x -axis.

To calculate joint moments or torques during locomotion, it is necessary to locate the point of force application dynamically. AMTI force platforms provide a direct measure of the moment around the mediolateral axis. However, the moment is referenced to an axis that is midway along the length of the platform and slightly below the top surface of the force platform. In the manual, this distance below the top surface is referred to as the origin; for our particular platform, the distance was 0.053 m. The treadmill elevated the point of force application by a distance 0.107 m above the surface of the force platform. As a result, both the vertical-force component (F_z) and the horizontal shear force (F_y) exerted by the subject contributed to the measured M_x . If the point of force application occurs at distance a along the length of the force platform from the M_x axis, then the equation for the moment is

$$M_x = (F_z \cdot a) + [F_y \cdot (0.107 + 0.053)]$$

By recording M_x , F_z , and F_y , it was simple to calculate a and thus locate the point of force application.

Using the following procedure, we verified that we could locate dynamically the point of force application. First, we affixed a small dot of reflective tape on the end of a sturdy wooden stick. With the treadmill belt in motion, a person standing on the side of the FTM pressed on the treadmill belt with the stick, applying a varying force with both vertical and horizontal components. The end of the stick naturally moved backward with the treadmill belt. As the force was applied via the stick, we recorded the force signals and simultaneously recorded videotape at 200 fields/s, synchronized with the force-data collection. Several additional small reflective dots identified the midpoint along the length of the platform and also provided a scale. Using the above equation, we calculated the point of force application. We also analyzed the videotape with a Peak 5 digitizing system. The video and force-platform data methods consistently identified nearly the same point of force application. Above a vertical-force threshold of 50 N, the two methods had a difference of <1 cm. The results from a sample calibration trial are shown in Fig. 2.

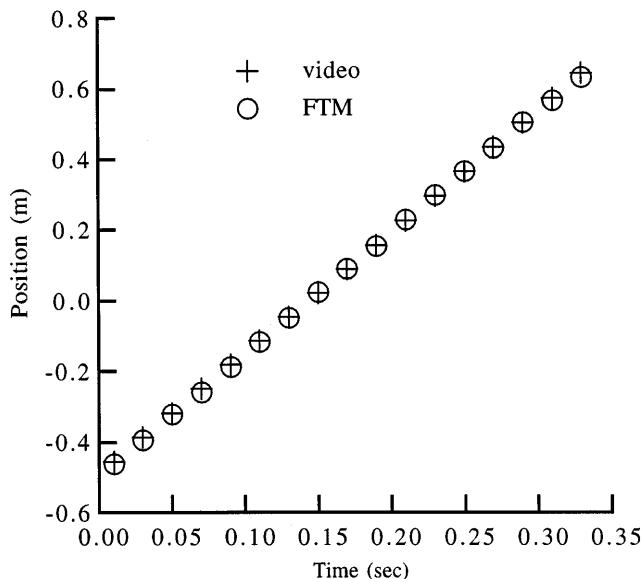


Fig. 2. Accuracy of the point of force-application determination. With treadmill running, we applied a time-varying force to the moving belt surface by using a sturdy wooden stick. We determined the position of the end of the stick by digitizing a high-speed video recording and by using the force-platform signals, as described in METHODS. Above a vertical force threshold of 50 N, the 2 methods gave results within 0.01 m of each other. The mean difference between the 2 methods was 0.002 ± 0.006 (SD) m. The two signals were highly correlated; $R^2 > 0.99$.

Natural frequency. Before proceeding to dynamic locomotion trials, we determined the unloaded natural frequencies of the FTM for F_z , F_y , and F_x . Using a wooden mallet, we gave the treadmill a sharp rap in the appropriate direction and collected the force signal at 1 kHz by using a Macintosh Quadra 650, National Instruments analog-to-digital board, and LabView4 software. To calculate the natural frequencies, we simply noted the time elapsed for 10 cycles of the ensuing “ringing” observed in the force traces. We found that the natural frequencies were >178 Hz for F_z , >87 Hz for F_y , and >88 Hz for F_x . The force platform without the treadmill had higher natural frequencies, as specified by the manufacturer (350 Hz for F_z , and 300 Hz for F_y and F_x). The addition of the treadmill mass and the compliance of the treadmill clearly decreased the resonant frequencies. Given that the natural frequency of the force platform alone in the vertical direction is 350 Hz, the added mass of the treadmill would theoretically reduce the overall resonant frequency to ~ 200 Hz. The actual natural frequency was 178 Hz; this indicated that the treadmill chassis was very stiff indeed. The more substantial drop in the natural frequencies in the horizontal directions appeared to be caused by the mass of the motor and the compliance in the mounting of the motor. However, the natural frequencies of the FTM were more than adequate for accurate recording of the ground-reaction forces of human locomotion.

Vibration and electrical noise. When the motor of the FTM was not turned on, we recorded little noise ($< \pm 3$ N for F_z , $< \pm 1$ N for F_y and F_x). When the motor was turned on (with no subject on the treadmill), we recorded noise amplitudes of ± 80 N on the F_z and ± 60 N

on the F_y and F_x signals. However, a fast Fourier transform (FFT) spectral power analysis of these signals revealed that 99% of this noise was at frequencies >46 Hz (see Fig. 3). The mediolateral forces applied by walking or running humans typically have peak magnitudes of only 5–10% of body weight (BWt; e.g., 70 N); thus the signal-to-noise ratio for F_x was poor. A large fraction of the vibration noise was due to flywheel imbalance. If measuring F_x were of particular interest, it may be technically feasible to do so with a precision-balanced flywheel.

Frequency content of ground-reaction force signals. To determine the frequency content of the ground-reaction force signals in a situation that is free of external vibrations, we had a subject walk (1.5 m/s) and run (3 m/s) over a conventional ground-mounted force platform (model LG6-4-2000, AMTI). We measured speed with a series of photocell beams placed along the runway. Five acceptable trials (average speed within ± 0.05 m/s) were saved for both walking and running. We considered these data to be virtually noise free. We then performed a FFT spectral power analysis of these force records. For walking, 99% of the integrated power content of both the F_y and F_z signals was <9 Hz. These values were similar to those reported previously (1). For running, 99% of the integrated power content of the F_z signal was at frequencies <10 Hz and $>98\%$ of the FFT power of the F_y signal was at frequencies <17 Hz. These spectral analyses are shown in Fig. 3. These analyses helped us choose appropriate filtering cut-off frequencies for processing our FTM data. We used a

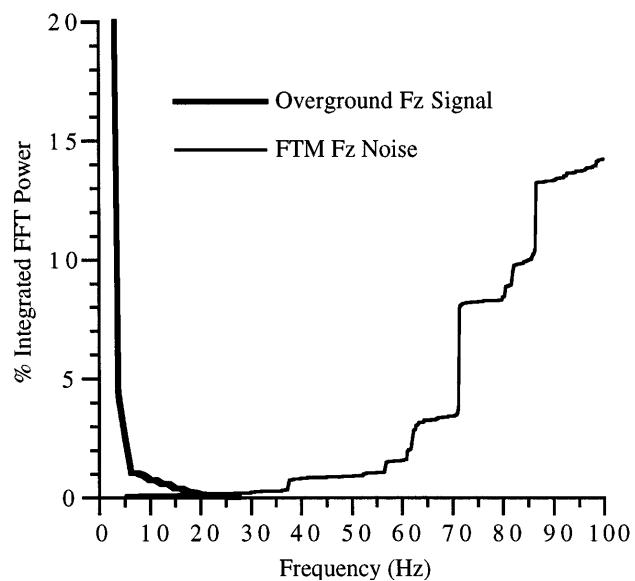


Fig. 3. Fast Fourier transform (FFT) power-spectrum analysis for ground-reaction force data and FTM vibration noise. Vertical ground-reaction force (F_z) data were obtained (at 1 kHz) during overground running at 3 m/s. We considered those data to be essentially noise free and representative of the true signal. FTM noise signals were obtained (also at 1 kHz) while operating the treadmill at 3 m/s with no subject running. Data were then transformed into the frequency domain by using a FFT; 99% of the signal power was <10 Hz, while 99% of the noise power was >46 Hz. Thus low-pass digital filtering of FTM data, with a cut-off frequency of 25 Hz, eliminated the noise without affecting the signal.

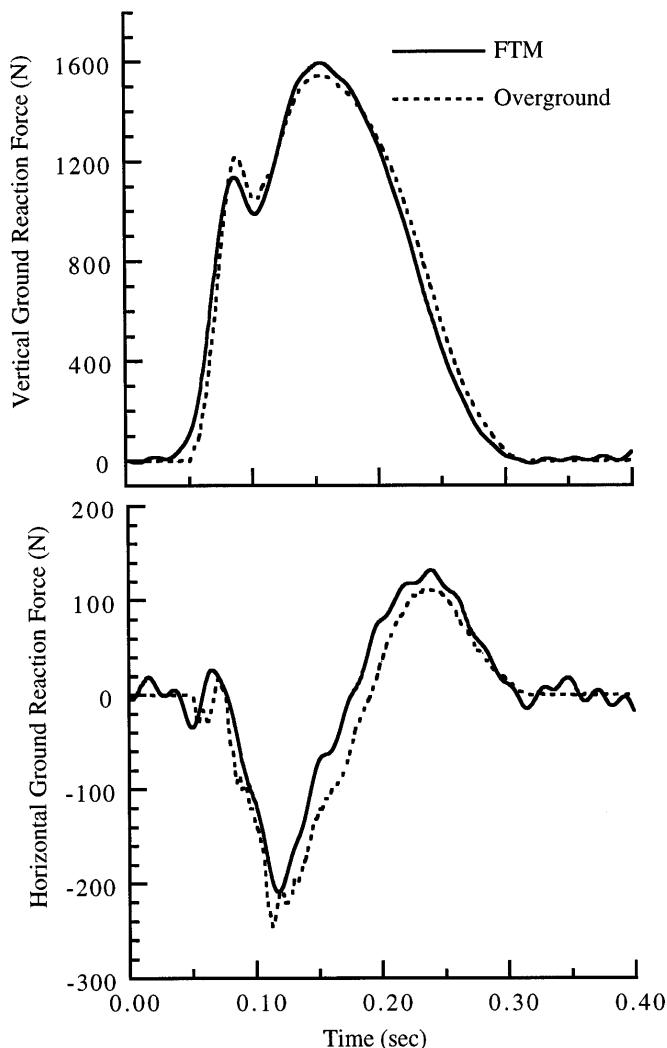


Fig. 4. Comparison of vertical (F_z , top) and horizontal (F_x , bottom) ground-reaction force signals obtained from FTM (solid line) and a force-platform runway (dashed line) for same subject when running at 3 m/s. FTM data were low-pass filtered at 25 Hz.

fourth-order low-pass Butterworth nonrecursive filter passed in both directions to effect zero-phase shift and a 3-dB cutoff of 25 Hz. We found that this eliminated 99% of the noise while retaining all of the important components of the signal.

Overall system tests. Next we performed some simple dynamic tests of the FTM to determine the overall accuracy of the system. The same subject walked and ran on the FTM at 1.5 and 3 m/s, respectively, while we collected F_z and F_y at 1 kHz. We filtered these data as described above. Over an integral number of strides, the average vertical force must be equal to BWt, and if the subject is maintaining the speed, the braking and propulsive ground-reaction impulses (force integrated over time) must be equal. We measured the average vertical force exerted over 10 successive, complete steps to be within 1% of BWt. We also compared the integrated horizontal-force signals for the first and second halves of the stance phase for the running trials. Averaged for 10 steps, the measured braking impulse was within 1% of the propulsive impulse. The roller

tachometer indicated that the treadmill speed was quite constant. With a subject walking at 1.25 m/s, the speed fluctuated by <0.02 m/s; for running at 3.0 m/s, fluctuations were <0.04 m/s.

FTM vs. overground measurements. We compared the FTM signals with the established methodology of a traditional runway-mounted force platform. We had a single subject run at 3 m/s on the FTM and across our force-platform runway. A comparison of the average values (from 10 steps) for various force magnitudes from the FTM vs. overground revealed only small differences caused by normal variation. The average peak vertical force (F_z) values were 1.78 vs. $1.83 \times$ BWt for the impact peak and 2.47 vs. $2.44 \times$ BWt for the active peak. The average peak braking (F_y) forces were -0.30 vs. $-0.35 \times$ BWt, and the average propulsive peaks were 0.21 vs. $0.20 \times$ BWt. A comparison of a typical running stride for the FTM vs. overground force-platform records is shown in Fig. 4. The signals obtained with the FTM were quite similar to those obtained overground. Because some stride-to-stride variability occurs, the traces were not identical. All of these values concurred with those in the literature (21).

DISCUSSION

From a purely mechanical perspective, steady-speed walking or running on an adequate motorized treadmill is identical to overground walking and running; the only difference is the frame of reference for each situation (23). Locomotion on a treadmill with inadequate power or momentum (i.e., no flywheel) does indeed differ from overground locomotion. However, on a treadmill with an adequate motor and flywheel, where the belt speed does not vary, the kinematics (21), ground-reaction forces (19), and metabolic cost (2) of locomotion are nearly indistinguishable from overground locomotion. As detailed above, our motor and flywheel appear to be adequate in maintaining a constant tread speed.

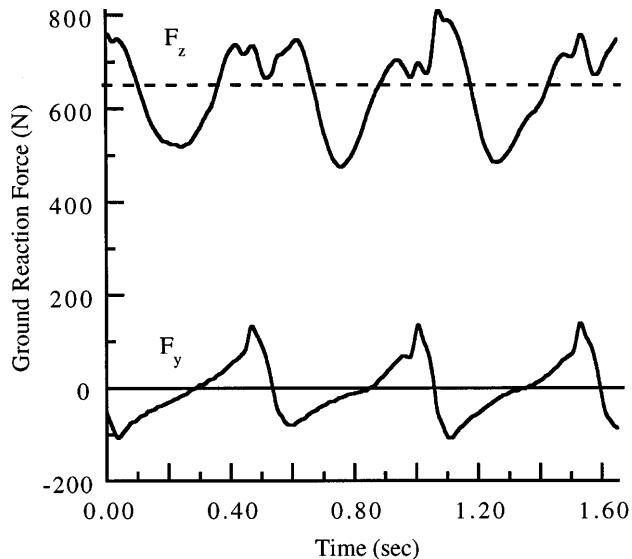


Fig. 5. Sample FTM data for subject walking at 1.25 m/s. Signals were low-pass filtered at 25 Hz. Dashed line, body weight.

FTMs provide many advantages over conventional runway-mounted force platforms. Our new FTM design now extends these advantages to many more studies of locomotion because we can measure the vertical and horizontal components of ground-reaction force and their moments. FTMs allow ground-reaction force data to be collected far more rapidly than do traditional runway studies (19). Furthermore, a large number of successive steps can be averaged to determine more representative values, thereby increasing statistical power. To adequately study running mechanics with a ground-mounted force platform system, a long laboratory or hallway space must be available. With a FTM, high-speed running studies can be conducted in very small laboratories. The modular design of the FTM allows the force platform and treadmill to be used independently of each other. That is an important point, because each item has considerable expense.

In addition to time and space savings, a FTM allows for experiments and treatments not possible with conventional runway-mounted force platforms. For example, with a FTM, it is possible to study the biomechanics of gait transitions (13), adjustments to perturbations of stability (5), and locomotion in simulated reduced gravity (16) or even microgravity (9). Furthermore, a FTM allows for simultaneous collection of biomechanical and other data (for example, rate of oxygen consumption or electromyography) without the use of telemetry. Dingwell et al. (11) have found that a FTM can provide useful feedback of vertical ground-reaction forces during rehabilitation of clinical patients who have amputations below the knee. In our own research, we find that the FTM is very useful as an ergometer that allows us to measure the mechanical work performed on the center of mass during locomotion (7). This is possible because the FTM records the summed ground-reaction force from both feet.

In Fig. 5, we show a typical force recording from the FTM for the same subject walking at 1.25 m/s. When humans walk, both feet are on the ground for at least part of the stride cycle. For some purposes, it is necessary to know the force under each individual foot. Davis and Cavanagh (8) and Dingwell et al. (11) have developed clever algorithms to separate the individual foot vertical forces for use with a FTM. These calculations rely on the location and velocity of the center of pressure to determine the time of single and double support. The same algorithms can be used with the present FTM design. Unfortunately, an equivalent algorithm cannot separate the horizontal forces for the individual feet in walking. This is because, during the double-support period, it is not possible to locate the point of force application (center of pressure) for the individual feet along the y -axis of the treadmill. Note that it is possible to locate very accurately the point of force application, and thus joint moments, during running and the single-support phase of walking. The FTM design of Belli et al. (4) uses two parallel treadmills, one for each foot. This allows for separate measurement of the individual foot horizontal forces, but it requires the subject to walk with an unnaturally wide stance. Thus

a perfectly acceptable method of measuring the horizontal forces exerted by the individual feet during the double-support phase of walking for repeated strides remains elusive.

In conclusion, the FTM described here can facilitate many types of biomechanical studies of human locomotion. Our device can accurately record the vertical (F_z) and horizontal (F_x) ground-reaction forces as well as the moments M_x and M_y . Induced vibrations prevented satisfactory measurements of F_x and M_z with the present device. This device can greatly decrease the time and laboratory space required for standard experiments and clinical evaluations.

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