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Abstract

This paper describes a method for testing in running shoes based on a test method for endurance testing of prosthetic feet (ISO 22675:2006). A specific step from human running motion was selected and processed to be feed into the test machine software. A motion capture system tracks the motion of the shoe and the machine. Forces and moments are acquired with a 6-DoF load cell. The test shows the capability of this approach to reproduce dynamics of heel-to-toe running motion. For this specific test scenario 60% of real time running speed was achieved while forces and moments were reproducible.

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1. Introduction

1.1. Background of work

There are diverse methods for sport shoe testing. By Odenwald (2006), the methods can be classified in subjective, biomechanical and mechanical test methods. To use the advantages of the different methods, a holistic approach in testing of sports equipment is suggested and methods of all three categories should be used in the
development process. Beside combinations of different test procedures, improvements can be achieved by implementing test characteristics and advantages from different methods.

To improve mechanical test setups by focusing on biomechanical input data for movement control or a more realistic loading of the shoe using special designed artificial test foot devices.

The aim of this study was to describe a machine setup that uses a standard test rig for prosthetic feet endurance tests that was adapted with biomechanical human running data to simulate a heelstrike running movement.

1.2. Test machines and test methods

There are various methods and machines to test shoes, some of these are easy available some are custom build according to requirements of customers. First test machines in shoe manufacturing were developed in the early 1930s. Miller (1938) mentioned the so-called Wheel of Torture by the U.S. National Bureau of Standards that performed one of the first human-like wear test for shoes. This kind of testing was developed over the years and is still in use for long-duration tests and quality tests in sports shoe industry today. Besides these machines, test rigs were developed which mainly consist of a vertical movement axis. Standard test methods for impact testing (e.g. ASTM F1976-06, DIN EN 23743) are reduced to this vertical loading and therefore only use simple stamps with a defined size. Denoth et al. (1985) demonstrated that results from simple material measurements (DIN 55305) have to be assessed critically if conclusions should be done to human movement. Heidenfelder (2010) described an improved dynamic test method using a modified heel stamp in a vertical compression test.

The design of prosthetic feet requires robust, biomimetic designs that interact harmonically with the user. User safety and to assure durability of these devices is of high interest as failure may cause injuries. Therefore a prosthetics testing ISO group introduced ISO 22675 in 2006 that describes a test standard to perform dynamic heel to toe walking for prosthetic feet. The related test machines have the following features in common: a rotating table that follows the shank angle curve and a second linear axis that pushes the prosthetic foot on the table to apply dynamic load during stance phase. The setup and dimensions of all components in the machine is described in the standard to allow for intended anterior and posterior forces as well as moments.

2. Material & Method

2.1. Running data

Running data were captured in a motion lab. A subject (m, 27 years, 72 kg) was instructed to run on a straight line passing two force plates (AMTI AccuGait, AMTI, Inc., Warren/MA, USA) at self-selected running speed with its own used shoes. The motion was captured via an optical tracking system (Qualisys AB, Goteborg, Sweden) with 9 cameras (Oqus 3+, Oqus 4). A Helen Hayes marker setup was applied on the subject with additional markers focusing on the rear, middle and front section of the running shoe (ASICS Gel TN771, size UK 9). Four rigid bodies were defined to analyze rotation angles in roll, pitch and yaw (Rearfoot, Midfoot, Forefoot and Shank).

2.2. Data processing

Synchronized motion and force data were recorded in Qualisys Track Manager (V 2.8) and exported as matrix file for further processing in MATLAB (R2013a, MathWorks, Inc., Natick/MA, USA). One single step with a stance time of 0.243 s (cp. Fig. 1) was selected following the criteria of the subject to hit the force plate right in center position, avoiding measurement errors as well. Shank in sagittal plane and vertical ground reaction force ($F_z$) was exported to control the test machine (data rate 1000 Hz).
2.3. ISO 22675 test machine and modification

For the test, a hydraulically driven machine (Shore Western KS2-07) that tests prosthetic feet according to ISO 22675:2006 was utilized. The machine consists of two individually controllable pistons. First piston (LP) presses the foot downward on a tilt table that is actuated by a second piston (RP) to allow for rotation in sagittal plane. The LP has a fixed uniaxial load cell with acceleration compensation to control forces on the test specimen. The RP has an angular sensor to control the second axis for synchronized motion. The prosthesis is attached to a prosthetic pylon that is displaced posteriorly to the LP. A spring loaded cam joint is located above to provide compensation of unwanted shear forces. The control system (RTAC) provides individually increased load on the prosthesis after each step to find the specified load after a startup phase. As the standard test machine setup restricts higher compensation of anterior-posterior forces due to the cam mechanism the setup was modified to allow for more degrees of freedom by help of a ball joint. Hence the setup is able to articulate around a ball that is reset in swing phase with rubber bands. To achieve damping behavior elastic foam was inserted. Furthermore as the setup of ISO 22675 was created for matching feet sizes, the increased size of the shoe covering the prosthetic foot has to be compensated by a posterior shift of the shank setup. At a specified position (500 mm height, 65mm anterior) a 6-DoF load cell was inserted working individually to the machine control algorithms.

The closed loop control of the machine uses the desired force curve as input parameter and modifies accordingly the dynamic stroke curve of LP. Therefore deformation characteristics due to different shoe designs as well as fatigue or wear of material can be detected as the LP curves alters during the cyclic test. As a result dynamic stiffness (force vs. stroke in N/mm), wear (LP curve from first cycle vs. last cycle) as well as material degeneration (characteristic points in the stroke or stiffness curve) through all load cycles can be observed. As a second benefit of the closed loop control every test specimen (shoe) is tested according to the same dynamic loading conditions. Therefore after assuring the same alignment and setup different samples can be tested and compared. Furthermore load curves can be modified according to specific load scenarios (walking, running, etc.).

2.4. Machine Test setup

Seven motion capture cameras are placed around the prosthetic test machine. The running shoe is put on the prosthetic foot (Soleus, size 26 cm, College Park Inc., Warren/MI, USA) with the same marker setup. The prosthetic connector is used to align the foot with the shoe to be in an upright position (90° +/- 0.2° to floor) in the unloaded state. Afterwards the specimen is mounted on the machine. The spring setup aligns the foot setup to hang in straight downward oriented position. The overall length of the assembly is adjusted by help of a tube clamp adaptor (Model 2W062, Wagner Polymertechnik, Silkerode, Germany) for an overall length of 700 mm.
3. Results

The input data was successfully transmitted to the machine and interpreted by the controls. The test specimen performed the desired heel-to-toe motion at the desired force values \( F_z \). Creating efficient motion and decrease unnecessary travel of the hydraulic pistons the shank angle was manually smoothed for swing phase.

3.1. Running Speed

Tests were performed with 20, 40, 50, 60 and 80% of real time speed. According to the test results all control were in a stable range from 20% until 60% (stance time 1.215 - 0.405 s) of real time running speed of the subject. At higher frequencies > 80% (stance time 0.304 s) the control algorithms were not fast enough to adapt for an accurate force curve. Furthermore dynamics detected by the acceleration sensor on the LP were high enough to engage the safety mechanisms of the machine.

3.2. Forces and Moments
Forces and moments are acquired of the 6-DoF load cell. The machine is controlled by a single component load cell that has acceleration compensation. Therefore force data of the machine is especially at higher speeds less noisy compared to the 6-DoF load cell due to inertia effects. In Fig. 4, forces and moments at slow velocity test (20%) are compared to high velocity test (80%). There are differences in the 80%-test between human input data and machine force data. With reduced movement velocities, the accuracy increases tremendously with nearly identical force output data in 20%-tests (correlation coefficient of $r = 0.99$). The accuracy of the loop control trying to follow the preferred kinetics and kinematics is reduced dramatically after 60% of real time motion ($r = 0.95$ in 80%-test).

![Human Fz vs. Machine Force](a)

![Human Fz vs. Machine Force](b)

![Force vs. Rotation in degrees](c)

![Force vs. Rotation in degrees](d)

Fig. 4. Force data in human versus machine tests compared for slow test with 20% (a, c) and fast tests with 80% of movement velocity (b, d)

**Motion**

Simulation of human movement by the machine is high precisely. There is no difference in shank movement simulation performed by RP during machine tests between the different movement velocities (cp. Fig. 4c-d). With regards to the shoe sole angle to the ground, machine data differs especially at initial contact due to a dorsal flexion movement of the prosthetic foot in this phase. The difference decreases in mid stance and late stance phase. There seemed to be only little influence on this effect caused by higher velocities (cp. Fig. 5). This soft heel characteristic is caused by the foot construction and could be influenced by a specific designed artificial foot for machinery shoe test setups.
Fig. 5. Movement angle of rearfoot rigid body in sagittal plane (pitch angle). Human running data versus machine data in a) slow (20%) and b) fast machine velocities (80%). The machine angle data are referenced to the RP

4. Conclusion

The overall setup and data of the presented test approach is reproducible and time efficient. Shear forces were found to follow not accurately but are related mostly to the used foot model. The test method is capable to perform heel-to-toe running at reduced speed (60% of real-time running speed). ISO 22675 is designed for endurance test and hence machines are suitable for endurance testing also for shoes. During analysis and post processing of the resulting data significant difference was found in force data that was used for input data. The test machine used the Fz force of the force plate. Comparing both coordinate systems reveals that a force measured at the shank (LP) would have to be a converted and transformed force vector of the force plate. Therefore we suggest for more realistic tests to use transformed forces as input data. Although maximum speed achieved within this study was about 60% of real time speed there are ways for optimization. For example the current control frequency (1 GHz) of the DAQ card that is down sampled by the operating system could be increase up to 2 GHz. Furthermore LP motions, speeds and accelerations were already at the machines maximum (660 mm/s). As a potential solution a curved surface on the tilt table might help to decrease these high piston travels when the prosthesis rolling over the plate the height would be compensated by the convex surface of the table. For this test we used a durable, state of the prosthetic foot model (College Park Soleus) but see high potential in more advanced foot models to provide more biomimetic gait and load distribution in the shoe. Pitch angle differences at heel and forefoot show that there is a difference between human foot and the prosthetic model. Regarding late stance, passive prosthetic feet will not be able to create toe flexion as well as a net positive push off for distributing realistic loads on the foot.

References


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