Medical Engineering & Physics 37 (2015) 151–155

Contents lists available at ScienceDirect

Medical Engineering & Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

A novel *in vivo* impact device for evaluation of sudden limb loading response

Erin Boutwell[a,b,c,*], Rebecca Stine[a,c], Steven Gard[a,b,c]

[a] Northwestern University Prosthetics-Orthotics Center Department of Physical Medicine and Rehabilitation, Feinberg School of Medicine, Northwestern University, 680 North Lake Shore Drive, Suite 1100, Chicago, IL 60611, USA
[b] Department of Biomedical Engineering, McCormick School of Engineering and Applied Science, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA
[c] Jesse Brown VA Medical Center, Department of Veterans Affairs, 820 South Damen Avenue, Chicago, IL 60612, USA

ARTICLE INFO

Article history:
Received 22 May 2014
Received in revised form 10 October 2014
Accepted 18 October 2014

Keywords:
Impact loading
Reaction forces
Lower limb
Shock transmission
Mechanical testing

ABSTRACT

The lower limbs are subjected to large impact forces on a daily basis during gait, and ambulators rely on various mechanisms to protect the musculoskeletal system from these potentially damaging shocks. However, it is difficult to assess the efficacy of anatomical mechanisms and potential clinical interventions on impact forces because of limitations of the testing environment. The current paper describes a new *in vivo* measurement device (sudden loading evaluation device, or SLED) designed to address shortcomings of previous loading protocols. To establish the repeatability and validity of this testing device, reliability and human participant data were collected while the stiffnesses of simulated and prosthetic limbs were systematically varied. The peak impact forces delivered by the SLED ranged from 706 ± 3 N to 2157 ± 32 N during reliability testing and from 784 ± 30 N to 938 ± 18 N with the human participant. The relatively low standard deviations indicate good reliability within the impacts delivered by the SLED, while the magnitude of the loads experienced by the human participant (98–117% BW) were comparable to ground reaction forces during level walking. Thus, the SLED may be valuable as a research tool for investigations of lower-limb impact loading events.

Published by Elsevier Ltd on behalf of IPEM

1. Introduction

The human musculoskeletal system is equipped to handle the large impact forces that occur during walking, running, and other common activities that involve limb loading. This shock absorption is provided through active mechanisms regulated by the neuromuscular system (such as joint configuration and muscle stiffness changes) [1,2] and through passive mechanisms comprised of the "natural" characteristics of soft tissue, bone, and cartilage [1]. However, the attenuation of these mechanisms may be insufficient when subjected to repetitive, high-frequency impact events such as those that occur during gait; this deficiency may result from the time response of the system or the sheer magnitude of the impact. High-frequency transient forces have been implicated in cartilage breakdown, degenerative osteoarthritis, and low back pain [3–5]. Therefore, much attention has been paid to the concept of introducing additional shock absorption into the limb system, particularly in situations where anatomical shock absorption is diminished or absent (*e.g.* osteoarthritis or lower-limb amputation). Attempts to augment shock absorption in affected individuals have often incorporated a change in shoe cushioning material or prosthetic components [6–8]. However, these types of interface interventions have not typically produced substantial changes in impact forces [6,7,9]. However, rather than a failure of the shock-absorbing intervention, this lack of effect may be a result of an inappropriate testing paradigm.

Most studies of shoe insole hardness or prosthetic stiffness have occurred in one of two settings: an *in vitro* benchtop testing environment or during a dynamic activity such as gait. There are significant limitations to such approaches. *In vitro* studies permit the systematic analysis of individual components of the limb system (shoe, foot, *etc.*), while neglecting the important contributions of system interactions. By contrast, dynamic studies (*e.g.* gait analyses, stepping down tasks) allow the investigation of the summed

---

* Corresponding author at: Northwestern University, Prosthetics-Orthotics Center, PM&R/Biomed Engr, 680 North Lake Shore Drive, Suite 1100, Chicago, IL 60611, USA. Tel.: +1 312 503 5730; fax: +1 312 503 5760.
E-mail addresses: e-boutwell@u.northwestern.edu, erinboutwell2015@u.northwestern.edu (E. Boutwell), rstine@northwestern.edu (R. Stine), sgard@northwestern.edu (S. Gard).

http://dx.doi.org/10.1016/j.medengphy.2014.10.008
1350-4533/Published by Elsevier Ltd on behalf of IPEM

effect of all components, but are unable to be controlled with the same level of precision. Thus, the need for a new technique for investigating impact loading of the limb is apparent.

Two *in vivo* techniques for investigating impact forces have been utilized to account for limitations of previous *in vivo* and *vitro* approaches by spanning the two testing environments. The first involves instrumented missile studies [10,11] in which participants are typically positioned with their femoral condyles against an immobile surface during a heel impact, which neglects the contributions of the knee and thigh to force transmission and attenuation. The second technique involves swinging participants into a wall-mounted force plate [12], and has been used to evaluate the effects of knee angle and surface stiffness on impact forces [13,14]. One drawback of this approach is the horizontal (*vs.* downward) orientation of the limb during impact. Additionally, the pendular nature of the technique requires a ceiling attachment to suspend the platform upon which the participant lies supine and adequate space to swing the pendulum.

The purpose of this study is to introduce a new device for investigating impact loading that incorporates realistic load levels, gravity-assisted downward movement of the body, and the contribution of the entire lower-limb system. The device was evaluated to assess its reliability as a method of delivering a consistent impact event.

2. Methods

A novel impact testing device was designed to allow for the assessment of impact forces on the *in vivo* lower-limb system. The Sudden Loading Evaluation Device (SLED) was constructed by modifying a commercially-available home gym system (Total Gym 1000, San Diego, CA). The system consists of a steel frame and a set of rails inclined 25° from the ground. An 8.7 kg platform translates up and down the set of rails on ball-bearing rollers. The commercial apparatus terminates with a baseplate, which was replaced with a force plate (AMTI OR6-5, Watertown, MA) (Fig. 1). The force plate (natural frequency: 360 Hz) was affixed onto a set of lightweight aluminum rails and a steel frame mounted directly onto a concrete floor; the stiffness of this attachment ($\sim$3000 N/mm) was estimated from rigid drop tests.

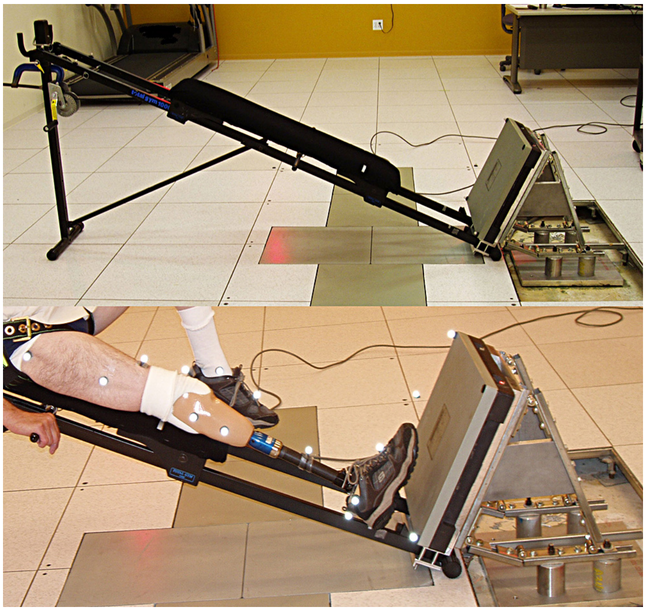

Fig. 1. SLED device with and without human subject.

2.1. Reliability testing

To assess the ability of the SLED to deliver consistent impacts, reliability testing was performed with a simulated limb created from a shock-absorbing prosthetic pylon (Endolite Telescopic-Torsion (TT) Pro, Blatchford, UK) and a wooden block “foot”. The TT Pro is a telescoping component that compresses a helical spring within the pylon housing, permitting easy modification to the stiffness of the simulated limb. The simulated limb was rigidly attached to the lower edge of the rolling platform such that it extended off the platform parallel to the device rails. The total mass of the simulated limb and rolling platform was 13.2 kg. The SLED was tested in a laboratory equipped with a twelve-camera digital real-time motion analysis system (Motion Analysis Corporation, Santa Rosa, CA). Retro-reflective markers were placed on the simulated limb, rolling platform, force plate, and SLED frame to track movement during testing.

Three experimental conditions representing varying stiffness levels (63 N/mm, 93 N/mm, and 115 N/mm) were evaluated to determine the ability of the force plate within the SLED apparatus to discriminate between the force responses of altered limb systems. A rigid condition, created by substituting a steel cylinder for the spring in the TT Pro, was also evaluated.

Each impact trial commenced with the simulated limb in contact with the force plate. A manually operated winch was used to raise the rolling platform and limb away from the force plate to attain a total displacement of 9 cm, calculated mathematically as the drop height required for an impact velocity comparable to reported velocities of the heel during level walking [15]. The quick release lever on the winch initiated a gravity-mediated fall of the rolling platform halted by contact of the simulated limb with the force plate. Force and marker position data were sampled at rates of 1920 Hz and 240 Hz, respectively. The reliability testing involved forty impact trials, 10 for each of the three stiffness levels & 10 for the rigid condition.

2.2. Human participant data

The consistency of the impact force and velocity is the primary concern in establishing the reliability of the SLED, and these variables can be assessed by means of the reliability testing previously described. However, because adding a human into the system will likely introduce greater variability, a human participant was recruited in an effort to provide initial evidence that consistency of the impact event can be maintained with a human in the system. Ethical approval was obtained from the governing institutional review board. A seventy year-old male participant (82 kg) with a unilateral transtibial amputation was positioned on the rolling platform with his prosthetic limb extended toward the force plate. The prosthesis was comprised of a patellar–tendon–bearing socket, a shock-absorbing pylon, a prosthetic foot, and a flat-soled canvas shoe. The sound-side limb was placed on an attached footrest to prevent it from interfering with the impact event, and the participant was instructed to keep their prosthetic leg extended. Limb position was maintained by straps above and below the knee. The procedures and experimental conditions were identical to those of the reliability testing trials. Twenty trials, five for each of the three stiffness levels & five for the rigid condition, were collected.

2.3. Data analysis

For both reliability and human participant data, kinematic marker data were post-processed in Cortex (Motion Analysis Corporation, Santa Rosa, CA). Subsequently, both marker and force data were filtered with a 4th order, zero-phase low pass Butterworth filter (cutoff frequencies of 15.625 and 125 Hz, respectively).