Medical Engineering and Physics 38 (2016) 581–585

Contents lists available at ScienceDirect

Medical Engineering and Physics

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

Comparison of three methods for identifying the heelstrike transient during walking gait

J. Troy Blackburn[a,b,c,*], Brian G. Pietrosimone[a,b,c], Matt S. Harkey[a,c], Brittney A. Luc[a,c], Derek N. Pamukoff[d]

[a] Neuromuscular Research Laboratory, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
[b] Department of Exercise and Sport Science, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
[c] Program in Human Movement Science, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
[d] Department of Kinesiology, California State University, Fullerton

ARTICLE INFO

Article history:
Received 18 November 2015
Revised 26 February 2016
Accepted 3 April 2016

Keywords:
Osteoarthritis
Impulsive loading
Cartilage
Knee
Loading rate

ABSTRACT

Impulsive, or high rate, loading contributes to cartilage degradation and is commonly identified via the heelstrike transient (HST) in the vertical ground reaction force (vGRF) during gait. Investigation of the HST may improve our understanding of knee osteoarthritis mechanical pathogenesis. However, the most appropriate method for objectively identifying the HST is unclear. Twenty-eight healthy subjects walked at a self-selected pace while vGRF data were captured. The efficacies of three HST identification methods (Radin, Hunt, and Modified Hunt) were evaluated using vGRF data lowpass filtered at three frequencies (raw/unfiltered, 75 Hz, and 50 Hz). Both the HST identification method and lowpass filter frequency influenced whether a HST was identified and whether a subject was classified as an “impulsive loader” (i.e. HST identified in 3 of 5 trials). The methods identified different phenomena in the vGRF, with the Radin and Modified Hunt methods identifying the HST 11-16 ms following ground contact and the Hunt method identifying the HST 83–122 ms following ground contact. Lowpass filtering the vGRF at 75 Hz and implementing the Radin method was the most effective approach for identifying the HST. Future longitudinal observations are necessary to determine if specific HST criteria are indicative of knee osteoarthritis development and progression.

1. Introduction

Knee osteoarthritis (OA) results from the gradual breakdown of articular cartilage, and is a leading cause of disability affecting 29 million Americans and encumbering an annual economic burden of $165 billion [1–3]. Loading rate influences cartilage health, with greater loading rates producing greater cartilage degradation [4–8]. Impulsive, or high rate, loading causes cartilage fibrillation, osteophyte formation, and decreased cartilage thickness, as well as altered biochemical function that are not noted with lesser loading rates [4,6,8,9]. Therefore, impulsive loading during gait is thought to contribute to development and progression of knee OA.

Given its cyclical nature and inherent role in human locomotion, walking gait offers an ideal model for evaluating factors that contribute to development of knee OA. Impulsive loading occurs when ground impact forces are distributed over a brief time interval (i.e. high rate loading), and is typically identified in the vertical ground reaction force (vGRF) during gait. The heelstrike transient (HST) refers to a rapid, transient rise in the vGRF immediately following ground contact during gait, and its presence and characteristics (e.g. magnitude and loading rate) are indicative of impulsive loading [10–12]. Evaluating the HST may enhance our understanding of the mechanical pathogenesis of knee OA. However, several methods/algorithms have been used to objectively identify the HST [10,12–15], and there is no consensus regarding the most appropriate approach.

The HST is typically identified from vGRF magnitudes and/or frequency content [10,12–15]. As such, the ability to objectively identify the HST could be influenced by high frequency noise and lowpass filter parameters. However, the most appropriate filter parameters and method for identifying the HST are unclear. The primary purpose of this investigation was to compare the efficacy of three methods for identifying the HST and classifying individuals as “impulsive loaders” (i.e. a HST is observed in the majority of walking trials). A secondary purpose was to evaluate the effects of lowpass filter frequency on HST identification.

* Corresponding author at: University of North Carolina at Chapel Hill, 124 Fetzer Hall, CB # 8700, Chapel Hill, NC 27599-8700, USA. Tel.: +1 919 8432021; fax: +919-962-0489.

E-mail address: troyb@email.unc.edu (J.T. Blackburn).

http://dx.doi.org/10.1016/j.medengphy.2016.04.008
1350-4533/

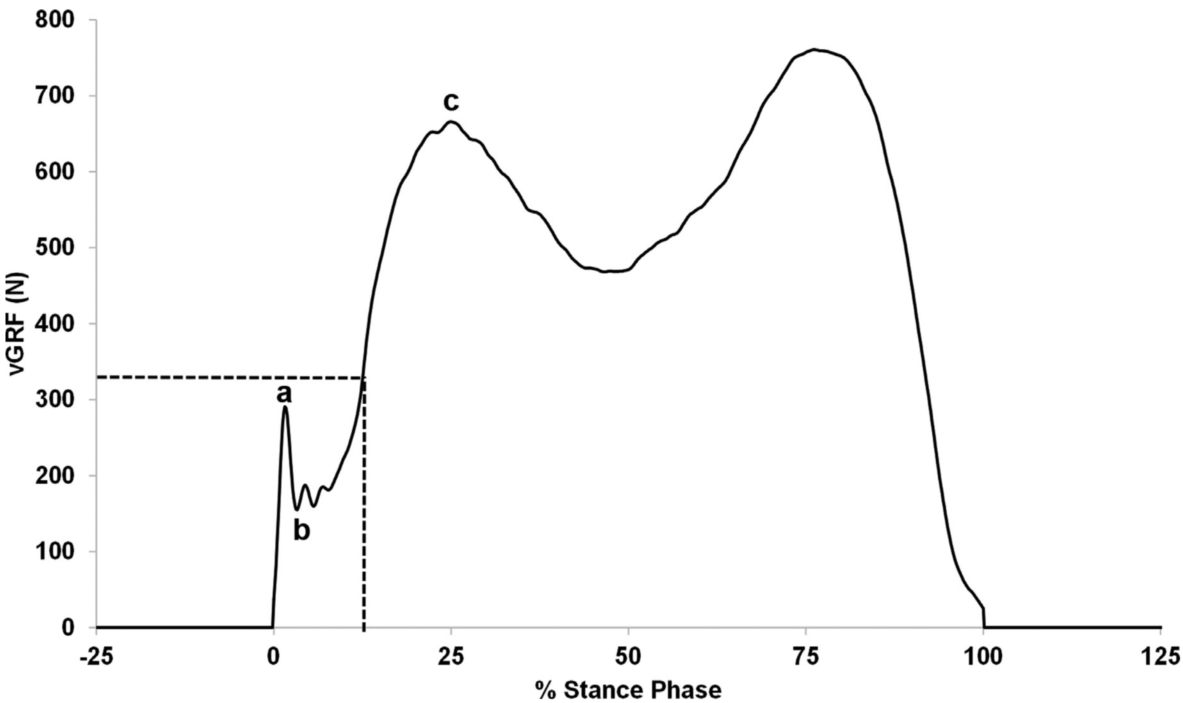

Fig. 1. vGRF vs. Time for a single trial (lowpass filtered at 75 Hz). HST was identified by evaluating the magnitudes of the vGRF peak immediately following ground contact (a) and the impending local minimum (b). For the Radin method, HST was identified as a/b ≥ 1.2. For the Hunt method, HST was identified if the difference between these magnitudes (a-b) was ≥ 0.5% of the overall peak vGRF during the first 50% of the stance phase (c), but analysis was restricted to values in the upper 50% of the overall vGRF peak (i.e. after the horizontal dashed line). The Modified Hunt method utilized the same identification criteria with the exception that the entire first 50% of the stance phase was evaluated.

2. Methods

Twenty-eight healthy individuals (22 females, 6 males) volunteered to participate (age = 20 ± 1 years, mass = 65 ± 10 kg, height = 1.70 ± 0.08 m). Subjects were included if they were 18–25 years of age and exercised at least 3 times per week for 30 min. Subjects were excluded if they had a history of lower extremity fracture, lower extremity joint injury resulting in time lost from daily activities in the 6 months prior to participation, or lower extremity orthopedic surgery. The study was approved by the university's biomedical institutional review board in accordance with The US Common Rule, and all subjects provided written informed consent prior to participation.

Ground reaction forces were sampled at 1000 Hz as subjects walked barefoot across a force plate (Bertec 4060-NC, Bertec Corp.) at a self-selected "comfortable" pace. Subjects walked 3 m prior to contacting the force plate and took at least 2 steps following contact with the force plate to avoid deceleration contamination of the vGRF. At least 5 practice trials were performed to ensure subjects could strike the force plate with the right foot without "aiming". Gait speed was monitored via infrared timing gates centered over the force plate spaced 1.2 m apart. Trials were deemed acceptable if the subject made contact with the entire foot on the force plate without noticeably altering his/her gait and if gait speed was within ± 5% of the practice trial average. Five acceptable trials were recorded for data analysis.

We compared two previously reported methods for identifying the HST [10,15]. Both methods identify the HST by evaluating the magnitudes of the vGRF peak immediately following ground contact and the impending local minimum (Fig. 1). Radin et al. [15] classified trials as possessing a HST if the ratio of these magnitudes exceeded 1.2 (Radin method). Hunt et al. [10] classified trials as possessing a HST if the difference in these magnitudes exceeded 0.5% of the overall peak vGRF during the first 50% of the stance phase (Hunt method). Additionally, Hunt et al. restricted their analysis to values above 50% of the overall vGRF peak. Preliminary analysis of our data indicated that the HST typically occurred immediately following ground contact, before 50% of the peak vGRF had been obtained. Therefore, we also evaluated a modified version of the Hunt method that evaluated the vGRF using the same criteria, but applied to the entire first 50% of the stance phase (Modified Hunt method). The stance phase was defined as the interval from ground contact (vGRF > 20 N) to toe off (vGRF < 20 N).

Frequency analysis of our data via Fast Fourier Transform revealed that the majority of the vGRF signal was contained below 10 Hz, but the upper end of the frequency spectrum was typically near 75 Hz. We also conducted a PubMED search using the terms "Gait and Ground Reaction Force and Knee" to identify the most common vGRF filter frequencies utilized for gait analysis related to knee pathology. The majority of publications did not report vGRF filtering characteristics, while others reported frequencies ranging 6–75 Hz, with the most common frequencies being 50 and 75 Hz [10,12,16–18]. It was unclear if those studies that did not report vGRF filter frequencies simply neglected to report this information or if they evaluated raw/unfiltered kinetic data. Therefore, we evaluated each HST identification method under lowpass filtering conditions (recursive 4th order Butterworth) that best represented the frequency content of our data and the most common procedures in the literature: raw/unfiltered, 75 and 50 Hz.

χ^2 analyses (3-way crosstabs) were conducted to evaluate the influences of identification method and filter frequency on the number of trials in which a HST was identified and the number of subjects identified as "impulsive loaders" (i.e. a HST identified in at least 3 of 5 trials). Significant χ^2 models were further evaluated to determine which levels of each independent variable (identification method and filter frequency) demonstrated the greatest departure from the expected frequencies as indicated by