Journal of Biomechanics 48 (2015) 1015–1022

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Stochastic description of the peak hip contact force during walking free and going upstairs

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ARTICLE INFO

Article history:
Accepted 29 January 2015

Keywords:
Femur
Hip contact force
Uncertainty
Loading

ABSTRACT

Uncertainty quantification for the response of a patient specific femur is mandatory when advocating finite element (FE) models in clinical applications. Reliable stochastic descriptions of physiological hip contact forces are an essential prerequisite for such an endeavor. We therefore analyze the in-vivo available data of seven individuals from HIP98 and OrthoLoad with the objective of characterizing the variability of the peak hip contact force magnitude and two corresponding spatial angles (in sagittal and frontal plane) during *walking free* and *going upstairs*. Regression analyses with linear mixed-effects models were performed resulting in six normal random variables, one for each force component and activity. Importantly, the statistical analysis accounts for the fact that *same* individuals performed both activities. The mean of the peak force magnitude was found to be linearly dependent on the body weight *with an additional, activity-specific intercept* and all variances were dominated by the inter-patient variability. No distinct correlation was found between the two angles and the force magnitude.

The proposed stochastic description of the peak hip contact force during *walking free* and *going upstairs* contributes towards future uncertainty quantification of patient-specific FE models.

1. Introduction

Simulations of the mechanical response of human femurs by finite element (FE) methods have been addressed for more than four decades (Brekelmans et al., 1972; Huiskes and Chao, 1983; Keyak et al., 1990; Yosibash et al., 2007). Despite recent achievements in verifying and validating patient-specific FE models by in-vitro experiments (Schileo et al., 2007; Cristofolini et al., 2010; Trabelsi et al., 2011), these models are rarely used in clinical practice to this day. A missing link with respect to the clinical applicability is the quantification of model uncertainties. Uncertainty quantification is an essential part of model validation (Oberkampf et al., 2004) and will increase the credibility and explanatory power of patient-specific FE models. Reliable FE models require three components: (a) geometry of the femur, (b) material properties and their spatial distribution, and (c) loading conditions (muscle and joint forces). Uncertainties are associated with all three model components and remain a major unexplored topic. In particular when modeling physiological loading conditions, assumptions have to be made on the magnitude and direction of the hip contact force. The applied force is usually representing an average loading condition (Bergmann et al., 2001), which was obtained by repeated in-vivo measurements with telemetric implants in multiple subjects. These in-vivo measurements imply a variability of the hip contact force not only between but also within subjects, which in turn raises the question of how this variability influences the results of a patient-specific FE model. Prior to that, a careful and rigorous *stochastic* description of the hip contact force is required.

The number of studies proposing a stochastic loading model for the human femur is limited (Nicolella et al., 2001, 2006; Grasa et al., 2005; Pérez et al., 2006; Viceconti et al., 2006; Long et al., 2009; Dopico-González et al., 2010), especially after restricting the literature research to three-dimensional models. Details of the models found in the literature are summarized in Table 1. Interestingly, every study investigated a quasi-static loading scenario and referred to peak forces measured in other experiments (with Bergmann et al. (2001) being cited most frequently) for either *walking free* or *going upstairs*. Although most of the stochastic loading models are based on the same data, the different number, types and characteristics of random variables demonstrate no consensus on how variability in loading should be modeled.

We therefore statistically analyzed data from the public databases *HIP98* (Bergmann, 2001) and *OrthoLoad* (Bergmann,

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http://dx.doi.org/10.1016/j.jbiomech.2015.01.041
0021-9290/

Table 1
Summary of stochastic loading models for the human femur.

Study	Activity	BW	Variable	Unit	Type	Mean	S.D.	COV (%)	Range[a]	Cited source
Nicolella et al. (2001, 2006)	Mid-stance phase of gait	–	Hip contact force – *X* component	N	Log-normal	1492	237.23	15.9	$[0, +\infty]$	Keaveny and Bartel (1993) and Kotzar et al. (1991)
			Hip contact force – *Y* component	N	Log-normal	915	408.09	44.6	$[0, +\infty]$	
			Hip contact force – *Z* component	N	Log-normal	2925	731.25	25.0	$[0, +\infty]$	
			Abductor muscle force – *X* component	N	Log-normal	1342	335.50	25.0	$[0, +\infty]$	
			Abductor muscle force – *Y* component	N	Log-normal	832	208.00	25.0	$[0, +\infty]$	
			Abductor muscle force – *Z* component	N	Log-normal	2055	513.75	25.0	$[0, +\infty]$	
Grasa et al. (2005) and Pérez et al. (2006)	Walking	–	Hip contact force – *Z* component	N	N/A	2029.58	130.02	6.4	N/A	Bergmann et al. (2001) and Heller et al. (2001)
	Stair climbing	–	Hip contact force – *Z* component	N	N/A	2153.06	14.55	0.7	N/A	
			Hip contact force – *X*, *Y* component	N	Deterministic; multiple of Z component					
			8 muscle forces	N	Deterministic; multiple of Z component					
Viceconti et al. (2006)	stair climbing	–	Body weight	N	Normal	690	160	23.2	[410, 1200]	Bergmann (2001) and Stea et al. (2002)
			Hip contact force	N	Deterministic; multiple of 'Body Weight'					
			3 muscle forces	N						
Long et al. (2009)	Normal walking	800 N	Hip contact force – Angle in-plane	deg	Normal	0	5.5	N/A	[−11,+11]	Bergmann et al. (2001, 1993)
			Hip contact force – Angle out-of-plane	deg	Normal	0	1.0	N/A	[−2,+2]	
			Hip contact force – Magnitude	N	Normal	N/A[b]	112	N/A	[mean±224]	
			Abductor muscle force – Magnitude	N	Normal	N/A[c]	200	N/A	[mean±400]	Paul (1966)
Dopico-González et al. (2010)	Normal walking	750 N	Hip contact force – Magnitude	N	Normal	1775	260	14.6	[1200, 2200]	Bergmann et al. (2001)
			Hip contact force – Angle *Y*	deg	Log-normal	90	30	33.3	$[0, +\infty]$	
			Hip contact force – Angle *Z*	deg	Normal	45	15	33.3	[0, 90]	
			8 muscle forces	N	Deterministic; fixed value					Duda et al. (1998)

[a] The range of a variable is equivalent to the support of its distribution type. In case of truncated random variables the range is set to the reported upper and lower threshold.
[b] Mean is related to the in-plane angle of the hip contact force by an unreported linear regression function.
[c] Mean is related to the magnitude of the hip contact force by an unreported linear regression function.

2008). Both databases contain in-vivo measurements of hip contact force magnitudes and directions for multiple patients performing various activities, among them *walking free* and *going upstairs*. We restrict our attention to these activities as they are considered to be the most common activities in daily life and as such are of importance for testing implants (Bergmann et al., 2010). Another reason is the larger number of public data compared to activities like falling or stumbling. These extreme activities are clinically relevant to femoral fractures, because the involved dynamics cause larger forces. Yet, real stumbling was observed only twice in Bergmann et al. (2004), whereas experimental attempts did not simulate the extreme activity in a realistic way. The scarcity of data for extreme activities limits a statistical analysis and motivates further research. Nevertheless, the same statistical method can be applied to all activities, if sufficient data is available.

A typical approach to characterize maximum values in other fields (e.g. maximum floods, earthquake strengths, insurance claims, etc.) is by fitting generalized extreme value (GEV) distributions (Fasen et al., 2014). In our case, this approach could be used to describe maximum force magnitudes from one patient. An analysis of pooled data from multiple patients, however, is not easily possible, as patients are statistically significantly different from each other. For this reason, we perform regression analysis with a linear mixed-effects model that considers part of the inter-patient variability as random effect.

Based on such a statistical analysis we propose a novel stochastic description of the peak hip contact force (magnitude and direction) during *walking free* and *going upstairs*.

2. Materials and methods

Databases used, retrieved files associated with *walking free* and *going upstairs* activities, and extraction procedures for determining the peak loads are presented in Sections 2.1 and 2.2. The statistical analysis is summarized in Section 2.3.

2.1. HIP98 and OrthoLoad

HIP98 and OrthoLoad are the result of Bergmann et al. (2001) and Heller et al. (2001), and contain in-vivo hip force data of seven patients (four in HIP98, all seven in OrthoLoad). Detailed information on the patients were collected from the Ortho-load manual (Bergmann, 2008) and related publications (Bergmann et al., 2001, 1993), and are summarized in Table 2. Every patient received either a type I (neck length = 60 mm, CCD angle = 135 deg) or a type II implant (neck length = 62 mm, CCD