A novel human "broomstick" forward fall model and its application in the strength analysis of the human upper extremity

Paweł Biesiacki, Dariusz Grzelczyk, Jerzy Mrozowski, Jan Awrejcewicz

Abstract: In this paper we consider a human forward fall model simulating the process of "falling like a broomstick" to the ground on the outstretched arms as the worst scenario of a forward fall. The biomechanical relationships between the hands and the ground are modelled by a non-linear impact law and the parameters of the model are estimated based on the scanned computer model of the human body as well as the experimental investigations performed with the help of the Optitrack motion capture system. The applied fall model allows to estimate time histories of ground reaction force in various scenarios of fall, and the obtained numerical simulations fit qualitatively and quantitatively other results presented in the literature. The obtained ground reaction force is used as a time-varying load condition in the finite element model of the human upper extremity created in Mimics software from computed tomography data. Finally, strength analysis of radius with two different fracture risk criteria is carried out, and the performed numerical analysis indicates that the strain criterion seems to be more useful for estimating the radius fracture site in comparison to the stress criterion.

1. Introduction

Falls belong to the common accidents in human daily life. The most upper extremity injuries occur as a result of a forward fall with direct impact on the extended arms [1]. Practically, all population groups are exposed to these risk factors, including children playing in the playground, teenagers practicing sports with high risk of injuries, adults performing activities related to their employment in an occupational environment, and the elderly during normal walking. As a result of fall, the risk to hands, torso, head, and/or other body parts of the human is possible. However, fractures of radial bone are the most common in eldery women with osteoporosis due to their compromised bone density/quality, and, probably, due to the increased risk of falling in this population group. The most common type of fracture of the radial bone is the so-called Colles' fracture as an injury of distal radius of a forearm [2]. The aforementioned Colles' fracture, as an injury of the radius, is a direct result of exceeding the maximum value of force allowable for this bone. For instance, Kim and Ashton-Miller used the value equal to 2400 N as a distal radius fracture threshold [3]. In other recent paper by Burkhart et al. [4], the estimated values of force causing fracture of the studied bones derived from cadavers were approximately equal to 2150 N. In this paper we considered a novel human “broomstick” forward fall model. Next, the obtained vertical ground reaction force (GRF) has been applied in the strength analysis of the human radial bone as an impact force.

2. Forward fall models – a brief literature review

Recent few decades have brought several models related to the impact of the human upper extremities to the ground as a result of a fall in forward or backward direction. The simplest model of the human falling motion is a single-degree-of-freedom (DoF) linear mass-spring-damper mechanical system subjected to sudden velocity input or impulse force input. This model can be extended to systems with many DoFs. A fall model proposed by Chiu and Robinovitch [5] applies to the human forward fall from a low height on the outstretched and fully extended upper extremity as the worst-case scenario of such a fall. This model is constructed based on a 2-DoFs lumped-parameter mechanical system containing elastic and damping elements. DeGoede and Ashton-Miller [6] used Adams software to develop a half-body, symmetric model of the human forward fall consisting of five segments (i.e. legs, torso with head and neck, upper arm, forearm and hand). The main goal of the authors of that paper was to study the possibility of injury of upper extremities among older women. Kim and Ashton-Miller [3] proposed another flat forward fall model as a two DoFs system constructed based on a mechanical double pendulum rotating freely around the pivot corresponding to the ankles of lower human extremities. The mechanical system was reduced to a system of linear translational movement with 2-DoFs with spring-damper elements responsible for attenuation action of the human muscles.

To conclude, it can be stated that the considered falling process was usually modelled based on flat and linear mechanical systems consisting of two rigid bodies with masses moved by transverse motion connected by linear spring-damper elements. These models were usually presented as a second-order ordinary differential equations of motion [5], or the equations written in the state space [3]. In the case of the more complex mechanical model, numerical simulations were performed only using commercial software [6]. In this paper we consider mathematical model of the human forward fall on the outstretched arms previously introduced in our previous paper [7]. On the contrary to the aforementioned reference, in this paper we applied more adequate a nonlinear model of impact at the wrist-ground interface, and kinematics of the faller during fall process were estimated using an Optitrack motion analysis system. Moreover, the obtained ground reaction forces have been applied as load conditions in the developed finite element model of the human radius analysed in Ansys.

3. The considered "broomstick" forward fall model

The human "like a broomstick" forward fall on the outstretched arms and human body parameters required for numerical simulation are presented in reference [7]. On the contrary to the previous paper, in this paper a non-linear model of impact at the wrist-ground interface has been applied to predict the vertical ground reaction force (GRF) $F_y(t)$. The applied model has the following form

$$F_y(t) = k_y \left| y(t) \right|^3 (1 - b_y \dot{y}(t)) \cdot \mathbf{1}(-y(t)), \tag{1}$$

where parameters k_y, b_y denote ground stiffness and damping coefficients in the vertical direction, respectively, and function $\mathbf{1}(-y(t))$ is the step function defined as

$$\mathbf{1}(-y(t)) = \begin{cases} 1 & \text{if} \quad y(t) < 0, \\ 0 & \text{if} \quad y(t) \geq 0. \end{cases} \tag{2}$$

This formulation of GRF had been used previously to model the heel strike in running [8] as well as to model GRF at the hand-ground interface in human fall model [6]. In our calculations we did not include the horizontal force component $F_x(t)$ which is required to prevent the hand from sliding.

The kinematic analysis of the faller during the fall process were observed using an Optitrack optoelectronic motion analysis system. The location of the individual markers on the faller's human body required to carry out the experimental observations are shown in Fig. 1. The selected frames from the recorded fall process in regular time intervals are depicted in Fig. 2.

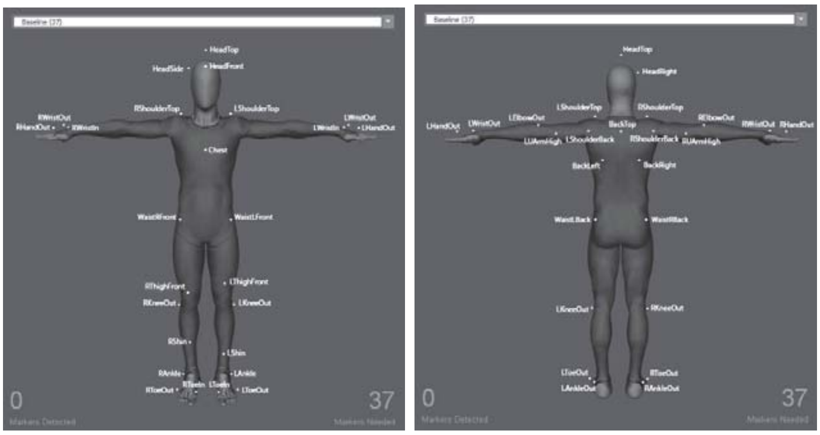

Figure 1. The location of the 37 passive reflective markers distributed on the faller's body: front view (on the left) and back view (on the right).

Figure 2. Forward fall from a standing position to the soft mattress observed by the Optitrack system using 37 passive reflective markers distributed on the faller's body.

The averaged time history of angle $\theta_2(t)$ (the angle measured between torso and arms) obtained from experiment for human walking speed v_0=1.5 m/s and its approximation are presented in Fig. 3.

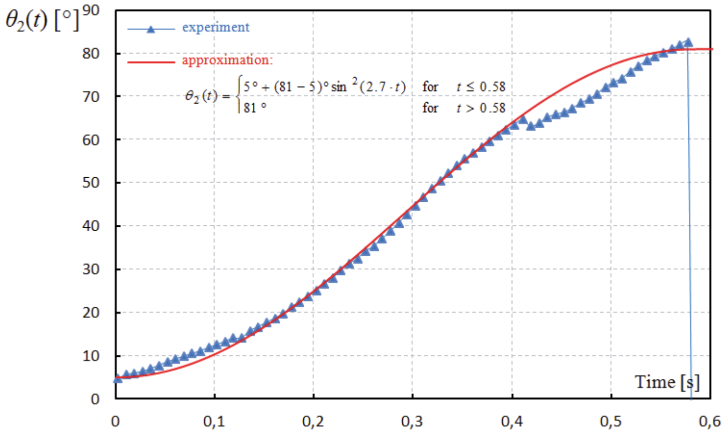

Figure 3. Time history of angle $\theta_2(t)$ obtained from the experiment (points) and its analytical approximation (curve) by analytical smooth function.

During numerical experiments we tested different values of the parameters k_y and b_y in order to obtain GRF which corresponds to the GRFs presented by DeGoede and Ashton-Miller [6]. In that paper, the authors tested five healthy young male volunteers aged between 22 and 28 years with the average body mass of 72±7 kg and the overall height of 173±3 cm [9]. Finally, the best degree of fit we obtained for k_y = 50 000 N/m^3 and b_y = 0.6 s/m.

4. Numerical simulation of the considered fall model

The results presented in Fig. 4 show the influence of different values of velocity v_0 on time histories of the force $F_y(t)$ acting on a single hand for ϕ_{Arm} = 15° (the angle between the arm and the vertical axis of the Cartesian coordinate system at the moment of the impact to the ground). For larger values of the parameter v_0, duration of the fall is smaller while the maximum value of GRF is greater. The value of GRF increases from 2246 N for $v_0 = 0.5\,\mathrm{m/s}$ to 2534 N for $v_0 = 2.0\,\mathrm{m/s}$. It means that for smaller speed v_0 (i.e. v_0 < 1.5 m/s), the GRF is less than the distal radius fracture threshold [3], whereas for larger values of v_0 (i.e. v_0 > 1.5 m/s) this threshold is exceeded.

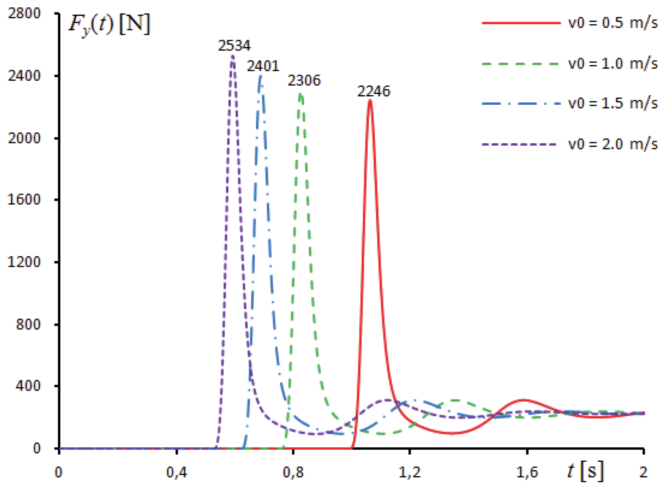

Figure 4. Time histories of GRFs $F_y(t)$ for $\phi_{\mathrm{Arm}} = 15°$ and different values of velocity v_0.

5. Finite element analysis of the radius

The DICOM data used in this paper come from cadaver of 35-years-old man with a height of 1.73 m and a weight of 75 kg. These data have been obtained using a Siemens 64 Slice computed tomography (CT) Scanner in the Department of Forensic Medicine, Jagiellonian University Medical College, Krakov, Poland. The DICOM file of the radial bone was imported to Mimics and the computer model of this bone was obtained and finally verified using *Fix Wizard* function (Fig. 5, on the left). As a result, a realistic 3D FE model of the radius consisting of 15751 FEs was obtained (Fig. 5, on the right). We used the SOLID185 FE-shaped tetrahedron element and isotropic material of the bone. Material inhomogeneity of the radius was also modelled in Mimics based on the CT images. As a result, mechanical properties of the considered radial bone were calculated using on the density-elasticity relationships proposed by Rho et al. [10]:

$$\rho = 1.067\mathrm{HU} + 131, \tag{3}$$

$$E = 0.004\rho^{2.01}, \tag{4}$$

where ρ [kg/m^3] represents density of bone, HU is the nondimensional Hounsfield Unit, E [MPa] denotes Young's modulus, while ν is Poisson's ratio. The obtained range of Young's modulus of the radial bone vary in the range 0.6-12 GPa, whereas Poisson's ratio equals 0.3 for all FEs.

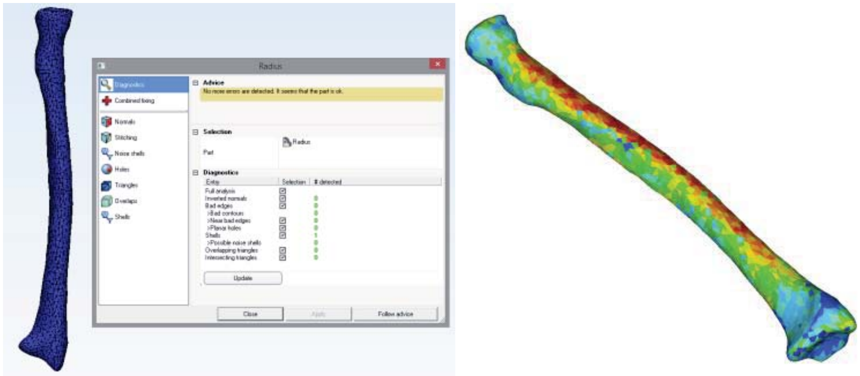

Figure 5. Meshed radial bone verified by *Fix Wizard* function in Mimics (on the left) and spatial distribution of inhomogeneous material properties (on the right).

Numerical results presented in Fig. 4, which correspond to the GRF for a straight position and the walking speed v_0 = 1.5 m/s, were used as load conditions of the developed FE model of the radius. In terms of boundary conditions applied in the analysed model of the radius, all six spatial DoFs in the proximal radius (region of the elbow joint) were fixed. The angle between the longitudinal axis of the radius and gravity direction was equal ϕ_{Arm}, while the GRF was applied in the region of the radial neck in the vertical direction (i.e. gravity direction).

In order to predict bone fracture sites, first the maximum von Mises stress, as a main criterion, has been used. Also the maximal strains of the bones, as another criterion, were calculated, for a better assessment of the radius fracture location and failure load value. The obtained results are presented in Fig. 6 as a both von Mises stress and strain distributions.

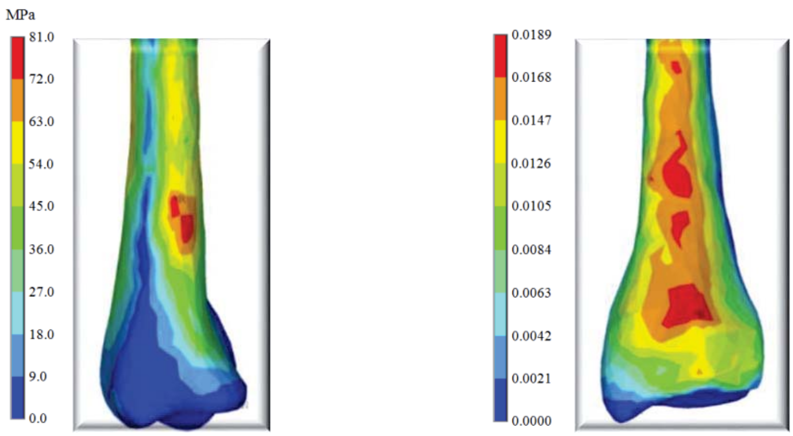

Figure 6. Finite element analysis of the radius bone: von Mises stress distribution (on the left) and strain distribution (on the right).

As can be seen, the maximum stress occur on the medial side (diaphysis) of the radius bone while the maximum strains occur in the distal region of this bone. Colles' fracture is the most common type of injury related to the forward fall on the outstretched arms. Therefore, the presented results indicate that the strain criterion can be more useful for estimating the radius fracture site, since the maximum strains are concentrated in the distal radius.

6. Conclusions

The fall model considered in this paper enables to estimate the vertical ground reaction force acting on the hands in different scenarios of the human fall, and the obtained numerical results agree with other results met in the literature [3]. The parameters describing the human body and modelling biomechanical properties between the palmar cartilages and the ground have a great impact on the obtained results. However, it should be noted that the developed model has also some limitations. Namely, the movement of the shoulder with respect of the torso and stiffness/damping properties of the shoulder joint have not been considered in this fall model. Nevertheless, the mentioned limitations may be of interest for our future study.

The obtained simulations showed that maximum values of the GRF that occur during a fall in forward direction on the outstretched upper extremities are sufficient to determine fracture sites and these results agree with numerical and experimental studies met in the literature [11]. Moreover, it has also been shown that the maximal strain criterion can be more useful for estimation of the fracture site than the von Mises stress criterion.

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Paweł Biesiacki, M.Sc. (Ph.D. Student): Lodz University of Technology, Department of Automation, Biomechanics and Mechatronics, 1/15 Stefanowski Str., 90-924 Lodz, Poland (*pawel.biesiacki@dokt.p.lodz.pl*). The author gave a presentation of this paper during one of the conference sessions.

Dariusz Grzelczyk, Ph.D.: Lodz University of Technology, Department of Automation, Biomechanics and Mechatronics, 1/15 Stefanowski Str., 90-924 Lodz, Poland (*dariusz.grzelczyk@p.lodz.pl*).

Jerzy Mrozowski, Ass. Professor: Lodz University of Technology, Department of Automation, Biomechanics and Mechatronics, 1/15 Stefanowski Str., 90-924 Lodz, Poland (*jerzy.mrozowski@p.lodz.pl*).

Jan Awrejcewicz, Professor: Lodz University of Technology, Department of Automation, Biomechanics and Mechatronics, 1/15 Stefanowski Str., 90-924 Lodz, Poland (*jan.awrejcewicz@p.lodz.pl*).