Forensic Science International 233 (2013) 220–229

Contents lists available at ScienceDirect

Forensic Science International

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

Biomechanical analysis of skull fractures after uncontrolled hanging release

Lionel Thollon [a,*], Maxime Llari [b], Lucile André [a,d], Pascal Adalian [c,d], Georges Leonetti [c,d], Marie-Dominique Piercecchi-Marti [c,d]

[a] Aix-Marseille Univ, LBA, 13916 Cedex 20, Marseille, France
[b] IFSTTAR, LBA, 13916 Cedex 20, Marseille, France
[c] APHM, CHU Timone, Service de Médecine Légale et Droit de la Santé, 13385 Cedex 5, Marseille, France
[d] Aix-Marseille Univ, UMR 6578, 13385 Cedex 5, Marseille, France

ARTICLE INFO

Article history:
Received 16 February 2012
Received in revised form 28 June 2013
Accepted 12 August 2013
Available online 29 September 2013

Keywords:
Forensic science
Skull fractures
Falls
Multibody dynamics
Finite element modeling
Hanging

ABSTRACT

In forensic research, biomechanical analyses of falls are widely reported. However, no study on falls consecutive to uncontrolled hanging release, when a hanging body is cut down, has ever been published. In such cases, the presence of cranial trauma can raise interpretation issues, and there may be doubt as to whether the fall was an accident or a crime disguised as suicide. The problem remains as to whether or not a fall after a free hanging release can lead to a skull fracture. To address this question, numerical simulations, post-mortem human subject tests and parametric studies were performed. We first recreated the kinematics and velocity of this atypical fall with post-mortem human subject tests and multibody simulations. We then tested the influence of biological variability on fracture production using a finite element model of the head. Our results show that fall severity depends largely on the direction of the fall. The risk of fracture is highest in the occipital region and with a backward fall. Our study also highlights the frequent occurrence of lower limb trauma in a free hanging release. Most importantly, we show that a fracture is produced in only 3.4% of falls that occur in a 10–90 cm height range. The overall findings of this study provide tools for pathologists and magistrates to decide on the most likely scenario and to justify further forensic investigations if required.

1. Introduction

Hanging is a very common method of suicide (the most frequent method in Istanbul and in Germany, and the second in the US) and a frequent topic in the literature [1–4]. These publications have mainly studied the sociology of hanging or atypical cases of suicidal hanging. Another aspect of research relates to homicidal hanging. Although it is rare, there is a wide range of published reports [5–7]. On cadaver examination after hanging, bruising on the distal parts of the upper or lower limbs is usually associated with impact with the surrounding environment. Cerebration and decortication can in fact produce violent body movements [8,9]. Observation of the crime scene provides essential information for interpretation. Bruising on proximal parts of the limbs requires a better understanding of prehension mechanisms. Furthermore, trauma of the cephalic region (scalp hematoma, skull fracture or meningeal hemorrhage) can be interpreted as a criminal hanging or as death by cranial trauma disguised as suicide. However, another explanation could be a post-mortem injury caused by a violent fall during release, because the body was not properly maintained during rope cutting. If this injury occurs close to the time of death, hemorrhagic areas may appear and imitate, in some cases, a vital mechanism. This raises the question of the possibility that this fall can lead to a skull fracture. We therefore need to understand how the impact of the head on the ground affects the injury produced, but to the best of our knowledge this question has never been studied.

The use of numerical human models to correlate trauma with mechanical impact conditions in forensic reconstructions of falls has been well documented [10–15]. Using these models, the impact can be studied as a dynamic mechanical problem subjected to a variety of factors. Features such as geometry, thickness, rigidity, number of sutures and density of the skull, representing biological variability, have been identified as influencing the formation of fracture [16,17]. Height and impact surface are also already known to influence the potential for injury and its severity [18–20]. Other factors, such as the subject's height and weight, representing anthropological variability, could also influence the

* Corresponding author. Tel.: +33 4 91 65 80 12; fax: +33 4 91 65 80 19.
E-mail address: lionel.thollon@ifsttar.fr (L. Thollon).

0379-0738/$ – see front matter
http://dx.doi.org/10.1016/j.forsciint.2013.08.015

kinematics and velocity of the fall. With the aim of understanding a free hanging release fall and its consequences on skull fracture production, we carried out numerical simulations of the fall using multibody software and a finite element model in parallel with post-mortem human subject (PMHS) tests. The multibody model and the PMHS tests enabled us to study the kinematics and velocity of the fall, while the 3D finite element model of the head helped to examine how skull fractures are produced in a fall on a flat surface.

The aim of our research was firstly to evaluate the effect of a number of parameters of the hanging body, such as anthropological variability, on the kinematics and velocity of the fall. Secondly, the aim was to evaluate the effect of biological variability of the skull on the mechanism of head injuries after impact in such atypical hanging. These findings could help a forensic pathologist to determine whether the conditions of a fall could have caused traumatic head impact injuries, and could help to eliminate any doubt as to the possibility of a criminal act prior to the hanging.

2. Materials and methods

2.1. Kinematics of free hanging release fall

To understand the kinematics of this unusual type of fall, PMHS tests and a multibody analysis were used. Use of numerical simulations avoids the need for a large number of cadavers, which is costly, and outcomes can be analyzed in relation to changes of various parameters [21,22]. PMHS tests yield information on the kinematics and acceleration of the fall. Numerical reconstructions of the fall were carried out using MADYMO® V7.1 software (Tass Safe, Eindhoven, The Netherlands). It is a software developed for application in engineering automotive safety research and improvement and used in other fields such as reconstruction of falls in forensic sciences [11,23,24]. This multibody approach uses numerical algorithms to predict the motion of systems of bodies connected by kinematics joints, based on initial conditions and the inertial properties of the bodies. It is assumed that this model of a human body has the same response to the environment as an actual human body.

A pedestrian model, developed by the University of Chalmers [25] and Faurecia [26] and validated by the Laboratory of Applied Biomechanics [27], was used for the study. This model initially represents a 50th percentile male (175 cm, 78 kg) which can be scaled easily to different heights and weights in order to represent human variability.

To understand the fall kinematics and to reconstruct it using the multibody model, two tests were first performed on a PMHS (PMHS 1 and 2). For these first two tests, the cadaver (1 m 60, 50 kg) was placed in suspension in the position of a body hanged with the knot under the chin (Table 1). Its falls from two different heights (50 cm and 70 cm, distance from the floor to the heel of the foot) were tested. The first height was consistent with the use of a stool and the second height with the use of a table. Accelerations of the head and pelvis were recorded with two sensors, one placed in the mouth of the model and the other in its right hip. Acceleration measures were used to calculate injury criteria for the head: the head injury criterion (HIC). Both tests (PMHS 1 and 2) were also video-recorded in order to coordinate the multibody model with cadaver falls.

From PMHS tests, the position and fall of the body were reconstructed using MADYMO® software. Because the pedestrian multibody model was conceived for rapid dynamics such as car accidents, it needed to be modified for a slow dynamic use like a free hanging release. To do so, all joints were modified to obtain a less rigid model with motion and response identical to those of the PMHS. Videos and acceleration recordings during the tests were used to fit the multibody model with PMHS test 1 to obtain the same kinematics during all the falls, the same acceleration of the head and pelvis, and the same HIC. The accelerations and injury criterion of PMHS test 2 were then compared with the multibody model. After correlation, two other tests (PMHS 3 and 4) on a cadaver (153 cm, 67 kg) were performed to verify that our model was consistent with different types of falls (Table 1). A fall from a height of 50 cm with the knot behind the neck and a sideways fall with the knot under the right ear were tested. The aim was to understand how the body falls on its side in order to check the accuracy of our multibody simulations. To ensure a sideways fall, the body was positioned at a slight angle, with the legs presumably maintained at five degrees from the perpendicular direction. After calibration using these four trials, we considered the model accurate and applicable to our parametric study.

2.2. Parametric study

This parametric study was performed using MADYMO® V7.1 software. The aim was to identify parameters which affect the fall and the area of the head which hits the ground. The height and weight of the subject were selected as parameters to study anthropological variability. The effects of fall height and ground damping were also studied. Because in hanging the knot may be in either a frontal, dorsal or lateral position [29], these three head positions were then included as a variable to understand their possible effect on the fall and on the production of skull fracture.

Furthermore, to analyze which area of the head is first impacted, potentially resulting in fracture [30,31], a finite element model of a human head was placed on our multibody model. This model was divided into 12 parts representing the right and left frontal, parietal, temporal face and mandible, high occipital and low occipital bones. Concerning the direction of the fall, in a real case, we considered that a body may fall either backwards, forwards or sideways depending on a combination of many incalculable factors. To avoid this, we chose to give the model a slight angle in order to force the direction of the fall. In this way we were able to study forward, backward or sideways falls under several parameters. This allowed us to investigate a wider series of conditions for a free hanging release on to a flat surface with a multibody model.

Once the parameters were chosen (Table 2), a complete parametric study with all these parameters was performed using HyperStudy® software (Altair Engineering, Inc., Detroit, MI, USA). HyperStudy® is a parametric tool intended for engineers and designers to improve their concepts and to optimize calculations. With HyperStudy® we planned a design of experiments (DOE) to test all the possible combinations of our study without writing and manually running all the combinations in MADYMO®· as HyperStudy® was able to run all the simulations independently. The results of these simulations yielded the effect of our parameters on the fall. The output data chosen were: impact forces, acceleration of the head, head HIC,, velocity of the head and part of the skull impacted.

A regression table from HyperStudy® was also obtained that quantified the effect of each variable on the kinematics of the fall. Data given by the HyperStudy® software were also compiled in an Excel® table, which was used to create distribution of responses, histograms and plots.

Subsequently, a second DOE was performed with the same variables and values except for fall height. Heights of 10, 20, 28 and 40 cm were tested to estimate the percentage of falls between 10 and 90 cm that reached the head impact velocity threshold leading to a skull fracture.

Table 1
PMHS tests.

Number	Test 1	Test 2	Test 3	Test 4
Weight of body	50 kg	50 kg	67 kg	67 kg
Height of body	160 cm	160 cm	153 cm	153 cm
Height of fall	50 cm	70 cm	50 cm	50 cm
Position of knot	Under chin	Under chin	Behind neck	Under right ear
Body angle	No	No	No	0.1 rad toward the right

Table 2
Study parameters: 6 variables and 3 values.

Variables	Height of subject	Weight of subject	Body angle	Position of head	Ground damping (coefficient)	Height of fall
Value 1	160 cm	50 kg	0.1 rad forward	knot under chin (backward head position)	0 (concrete)	50 cm
Value 2	170 cm	65 kg	0.1 rad backward	knot behind neck (forward head position)	500 (intermediate absorbing ground)	70 cm
Value 3	180 cm	80 kg	0.1 rad on the right side	knot under left ear (sideways head position)	1000 (padded ground)	90 cm