Journal of Biomechanics 47 (2014) 1749–1756

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Normalizing and scaling of data to derive human response corridors from impact tests

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ARTICLE INFO

Article history:
Accepted 6 March 2014

Keywords:
Biofidelity
Corridors
Dummies
Post-mortem human subjects
Military and automotive loading
Normalization
Scaling
Impact response

ABSTRACT

It is well known that variability is inherent in any biological experiment. Human cadavers (Post-Mortem Human Subjects, PMHS) are routinely used to determine responses to impact loading for crashworthiness applications including civilian (motor vehicle) and military environments. It is important to transform measured variables from PMHS tests (accelerations, forces and deflections) to a standard or reference population, termed normalization. The transformation process should account for inter-specimen variations with some underlying assumptions used during normalization. Scaling is a process by which normalized responses are converted from one standard to another (example, mid-size adult male to large-male and small-size female adults, and to pediatric populations). These responses are used to derive corridors to assess the biofidelity of anthropomorphic test devices (crash dummies) used to predict injury in impact environments and design injury mitigating devices. This survey examines the pros and cons of different approaches for obtaining normalized and scaled responses and corridors used in biomechanical studies for over four decades. Specifically, the equal-stress equal-velocity and impulse-momentum methods along with their variations are discussed in this review. Methods ranging from subjective to quasi-static loading to different approaches are discussed for deriving temporal mean and plus minus one standard deviation human corridors of time-varying fundamental responses and cross variables (e.g., force-deflection). The survey offers some insights into the potential efficacy of these approaches with examples from recent impact tests and concludes with recommendations for future studies. The importance of considering various parameters during the experimental design of human impact tests is stressed.

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1. Introduction

Human cadaver (Post-Mortem Human Subjects, PMHS) tests using various loading devices are routinely used to determine responses to impact loading for crashworthiness applications including civilian (motor vehicle) and military environments. Loading devices include: sled and electrohydraulic piston equipment, an impacting mass (pendulum device) attached to a device such as pendulum, and drop tests of the PMHS (Kallieris et al., 1981; Cavanaugh et al., 1990; Yoganandan et al., 1996; Pintar et al., 1997; Yoganandan et al., 2001; Yoganandan et al., 2007a). Injuries produced in the laboratory from these devices are compared with field crash data. They are also used to determine injury mechanisms as applied loads are known and other variables are measurable. Fundamental outcomes (time-varying accelerations, forces and deflections) from these experiments are used to develop biofidelity corridors for crashworthiness applications. They are needed to calibrate/evaluate anthropomorphic test devices (dummies) to mimic human impact responses (Backaitis and Mertz, 1994; Kuppa, 2004). The dummy response should fall within variations of the human responses; this variation is described in the form of response corridors/envelopes.

Responses from individual surrogate tests can be directly grouped to determine the mean and standard deviations if inter-specimen variability can be ignored or minimal. This is not uncommon in biomechanics studies (Stemper et al., 2004; Yoganandan et al., 2004; Yoganandan et al., 2007b; Lessley et al., 2010). However, the inherent biological variability of the human limits the applicability of this approach to derive corridors for assessing dummy biofidelity. Physical (mass and stature), geometrical, material and inertial properties affect biomechanical responses, and in almost all PMHS impact tests, it is difficult to control subject selection such that all variables are confined to a small range. For data to be applicable to a specific dummy anthropometry/size, it is necessary to normalize individual subject responses to a predetermined standard/reference (example, mid-size dummy total body mass) population. Subsequent to the conversion of measured specimen-specific data to standard responses,

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http://dx.doi.org/10.1016/j.jbiomech.2014.03.010
0021-9290/Published by Elsevier Ltd.

means, standard deviations and human response corridors can be derived, and this process leads to the establishment of dummy biofidelity corridors. Scaling is a process by which normalized responses and corridors can be converted from one standard to another (example, mid-size adult male to large-male and small-size female adults, and to pediatric populations). While many studies using these processes exist in impact biomechanics literature, a review has not been conducted on this topic. This is the objective of the present survey article. Specifically, methods used for normalizing and scaling and deriving corridors are presented in brief, and their pros and cons are discussed with recommendations for future experimental studies.

2. Equal-stress equal-velocity method

2.1. Description

This approach is simple and straightforward (Eppinger, 1976). It assumes linear relationships between the length, mass and time units, and described by the following Eqs. (1–3).

$$L_s = \lambda_l * L_m \tag{1}$$

$$M_s = \lambda_m * M_m \tag{2}$$

$$T_s = \lambda_t * T_m \tag{3}$$

Where, subscripts m and s refer to the tested PMHS and the standard reference; L, M and T refer to the length, mass and time; and λ refers to the fundamental scaling factor. The equal-stress equal-velocity method further assumes identical density and modulus of elasticity between the mass and prototype (dummy for automotive applications). This assumption results in Eq. (4), where the density variable, ρ has the units of mass divided by volume (mass/length cube).

$$\rho_m = \rho_s \tag{4}$$

Eqs. 1–3 combined with the density eq. 4, results in eqs. 5 and 6.

$$\frac{M_m}{L_m^3} = \frac{M_s}{L_s^3} = \frac{\lambda_m * M_m}{\lambda_l^3 * L_m^3} \tag{5}$$

$$\lambda_l = \sqrt[3]{\lambda_m} \tag{6}$$

Eqs. 1–3 combined with the modulus of elasticity E (7), results in Eqs. (8) and (9). It should be noted that force divided by area (product of mass and length divided by the product of the squares of time and length) is the unit of this variable.

$$E_m = E_s \tag{7}$$

$$\frac{M_m * L_m}{T_m^2 * L_m^2} = \frac{M_s * L_s}{T_s^2 * L_s^2} = \frac{\lambda_m * M_m * \lambda_l * L_m}{\lambda_t^2 * T_m^2 * \lambda_l^2 * L_m^2} \tag{8}$$

$$\lambda_t^2 * \lambda_l = \lambda_m \tag{9}$$

Substituting Eq. (6) into Eq. (9) results in

$$\lambda_t^2 * \lambda_l = \lambda_l^3 \tag{10}$$

$$\lambda_t = \lambda_l \tag{11}$$

Eq. (11) indicates that factors for the time and length are the same. The force (units of mass times length divided by time squared) force factor is

$$\lambda_F = \frac{F_s}{F_m} = \frac{M_s * L_s / T_s^2}{M_m * L_m / T_m^2} = \frac{\lambda_m * M_m * \lambda_l * L_m / \lambda_l^2 * T_m^2}{M_m * L_m / T_m^2} = \lambda_l^2 \tag{12}$$

$$F_s = \lambda_l^2 * F_m \tag{13}$$

Using the above equations, and the mass of each PMHS and mass of the prototype, the following equations show the normalization factors for the force, displacement, time and acceleration to convert specimen-specific data to prototype/reference data.

$$\text{Normalizing factor for force} = \lambda_m^{2/3} \tag{14}$$

$$\text{Normalizing factor for deflection} = \lambda_m^{1/3} \tag{15}$$

$$\text{Normalizing factor for acceleration} = \lambda_m^{-1/3} \tag{16}$$

$$\text{Normalizing factor for moment} = \lambda_m \tag{17}$$

$$\text{Normalizing factor for time} = \lambda_m^{1/3} \tag{18}$$

2.2. Applications

As can be appreciated, all normalization factors are based on the total body mass of the tested PMHS and they do not depend on the type of test or the specific body region (example, thorax and abdomen). This is the unique advantage of this normalization method. Because of its simplicity/adaptability, this approach has been used in numerous studies. For example, early applications involved normalization of upper torso seatbelt forces in frontal impacts to account for variations in PMHS mass, from more than 100 tests (Eppinger, 1976). Total body mass ranged from 36 to 102 kg. A later application of this approach consisted of normalizing data from 49 PMHS side impact tests (mass ranged from 46 to 102 kg) with varying velocities and boundary conditions (rigid and padded) (FMVSS-214, 1990; Eppinger et al., 1984). This method has also been used in recent side impact studies for applications to the mid-size ES-2re and small-size SID-IIs dummies (Kuppa, 2004). Forty-two PMHS sled tests conducted at the Medical College of Wisconsin were used to normalize data to the standard mass of the two different dummies, 75 and 48 kg, respectively (Pintar et al., 1997; Maltese et al., 2002; Kuppa et al., 2003; Kuppa, 2004). The current update of the FMVSS-214 standards incorporates these analyses (FMVSS-214, 2008). Other applications included normalizing side impact sled test data to small-size female dummy mass to obtain acceleration, force and deflection responses for evaluating the biofidelity of 5th percentile anthropomorphic test devices (Yoganandan and Pintar, 2005). This method has also been used in more recent studies. For example, Yoganandan et al. used this approach to determine the force-time histories from oblique side impact sled tests wherein data from five PMHS were obtained from load cells attached to anthropometry-specific modular load walls (Yoganandan et al., 2013). In order to accommodate additional factors and for region-specific normalizations, the impulse-momentum method has been used and this is described below.

3. Impulse-momentum method

This method accommodates specific body region/segmental characteristics and the type of the impact test for determining normalizing factors (Mertz, 1984). Mass and stiffness ratios are used along with assumptions of spring-mass models. Sled tests and whole body free fall/drop tests are treated as one degree-of-freedom mass-spring system while pendulum tests are treated as two-mass spring systems because of its finite mass. The one- and two-mass spring systems are described below using examples.

3.1. One degree-of-freedom system

In a side impact sled test with a segmented wall accommodating thorax, abdomen and pelvic load plates, a portion of the total body mass of the PMHS loads each plate. These portions are termed