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Short communication

Determining the optimal system-specific cut-off frequencies for filtering *in-vitro* upper extremity impact force and acceleration data by residual analysis

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ABSTRACT

The fundamental nature of impact testing requires a cautious approach to signal processing, to minimize noise while preserving important signal information. However, few recommendations exist regarding the most suitable filter frequency cut-offs to achieve these goals. Therefore, the purpose of this investigation is twofold: to illustrate how residual analysis can be utilized to quantify optimal system-specific filter cut-off frequencies for force, moment, and acceleration data resulting from *in-vitro* upper extremity impacts, and to show how optimal cut-off frequencies can vary based on impact condition intensity. Eight human cadaver radii specimens were impacted with a pneumatic impact testing device at impact energies that increased from 20 J, in 10 J increments, until fracture occurred. The optimal filter cut-off frequency for pre-fracture and fracture trials was determined with a residual analysis performed on all force and acceleration waveforms. Force and acceleration data were filtered with a dual pass, 4th order Butterworth filter at each of 14 different cut-off values ranging from 60 Hz to 1500 Hz. Mean (SD) pre-fracture and fracture optimal cut-off frequencies for the force variables were 605.8 (82.7) Hz and 513.9 (79.5) Hz, respectively. Differences in the optimal cut-off frequency were also found between signals (e.g. *Fx* (medial–lateral), *Fy* (superior–inferior), *Fz* (anterior–posterior)) within the same test. These optimal cut-off frequencies do not universally agree with the recommendations of filtering all upper extremity impact data using a cut-off frequency of 600 Hz. This highlights the importance of quantifying the filter frequency cut-offs specific to the instrumentation and experimental set-up. Improper digital filtering may lead to erroneous results and a lack of standardized approaches makes it difficult to compare findings of *in-vitro* dynamic testing between laboratories.

1. Introduction

Impact testing of biological structures requires a cautious approach to signal processing, specifically digital filtering. The frame of the impact device, the impactor, the instrumentation and the characteristics of the specimens (e.g. length, potting medium, bone density; Cain, 1987) are all potentially subject to resonance, which is represented in the signal as noise (Burgin and Aspden, 2007). While careful planning and experimental design can help minimize noise, it will still be present due to the fundamental nature of the impact process itself (Cain, 1987; Zhou, 1998; von Gierke and Brammer, 2002).

In-vitro impact testing has generally been used to determine the fracture strength of bone in response to loads that are indicative of a forward fall (Troy and Grabiner, 2007) or automobile accidents (Duma et al., 2003). Much of the research in this area has not reported the filtering processes used (Moore et al., 1997; Greenwald et al., 1998), or has not provided a meaningful rationale regarding the chosen frequency cut-offs (Kim et al., 2006). The lack of quantification and reporting of filtering characteristics makes comparisons of data and the development of injury criteria difficult (Stitzel et al., 2002).

The Society of Automotive Engineers (SAE) *standard J211-1—Instrumentation for impact test—Part 1—Electronic instrumentation* (SAE International, 2007) recently included a standard for filtering upper extremity impact data. This recommendation is based on information provided by Stitzel et al. (2002), who, using a Butterworth filter, recommended a cut-off frequency of 600 Hz for all force and acceleration data. While this recommendation brings attention to the lack of filtering guidelines for upper

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extremity impacts, there are significant limitations in adopting this type of "blanket approach" to signal filtering. Suggesting that one filter cut-off frequency is adequate for all recorded signals within and between testing set-ups does not adequately address a total system approach philosophy (Grenke, 2002). Furthermore, this approach does not address instrumentation or procedural differences between laboratories and does not take into consideration the changes in resonance of the equipment, specimens, and instrumentation that may occur from increased impact intensity.

Therefore, the purpose of this investigation is twofold: (i) to illustrate how residual analysis can be utilized to quantify optimal system-specific filter cut-off frequencies for force and acceleration data resulting from *in-vitro* upper extremity impacts, and (ii) to show how cut-off frequencies can vary based on impact condition intensity.

2. Methods

Eight human fresh-frozen cadaver radii specimens (4 male, 4 female; 5 left, 3 right; mean (SD) age 61.0 (9.7) years), cleaned of all soft tissues, were potted at a 75° angle in the sagittal plane (Greenwald et al., 1998). Specimens were securely clamped into the impact testing system (Fig. 1) and positioned such that the distal end of the radius rested against a model scaphoid and lunate composed of high density polyethylene (Sawbones, Pacific Research Laboratories Inc., Vashon, WA). The lunate and scaphoid were attached to a six-degree of freedom load cell (however, no torsional component was measured) with a capacity of 20 kN (natural frequency >6 kHz; Denton Femur load cell, Model # 1914A, Robert A. Denton Inc., Rochester Hills, MI), which in turn was rigidly connected to an impact plate (Fig. 1).

Two tri-axial accelerometers (MMA1213D and MMA3201D, Freescale Semiconductor, Inc., Ottawa, ON, Canada) with a range of ± 100 g were firmly glued (M-bond 200; Vishay Micro-Measurements) to the bone using procedures commonly used for attaching strain gauges (Staebler et al., 1999). A 250 g uni-axial accelerometer (iMEMS®, ADXL193, Analog Devices Inc., Norwood, MA) was attached to the impact plate. The bone-mounted accelerometers were attached distally (dorsally, proximal to the radial styloid) and proximally (volar aspect, where the bone protruded from the potting jig) aligned with the bone's long axis. Acceleration data from two directions at each location are presented: parallel to the long axis of the forearm (axial direction), and normal to the axial direction in the volar/dorsal direction (off-axis direction).

Impulsive loads were applied with a custom designed pneumatic impact system (Quenneville et al., 2010) and were energy controlled as a function of velocity (2.0 m/s–4.0 m/s; constant impactor mass of 6.8 kg). Loading was repeated starting with an initial impact energy of 20 J and increasing in 10 J increments, until fracture. All data were collected simultaneously by a custom LabVIEW program (LabVIEW 2009, National Instruments, Austin, TX) at 15 kHz.

The original force and acceleration signals were filtered with a dual pass, 4th order Butterworth filter at 14 cut-off frequencies (no filter, 60, 80,100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, and 1500 Hz). Cut-off frequencies were selected to systematically span the filter recommendations (180 Hz, 600 Hz, and 1000 Hz) tested by Stitzel et al. (2002). Once filtered, residual analyses were conducted (Winter, 2005) to quantify the optimal cut-off frequency (Fig. 2) for the first (pre-fracture) and last (fracture) trials collected for each specimen. The peak forces and accelerations at each cut-off frequency were then determined.

One-way repeated measures ANOVAs were used to analyze differences in the optimal cut-off frequencies for the pre-fracture and fracture trials for all peak force and acceleration variables. Two-way (2 trials (pre-fracture and fracture) X 14 cut-off values) mixed repeated measures ANOVAs were conducted to explore differences in the peak force and acceleration variables. Significant interactions were further analyzed with Tukey's HSD post-hoc test. Statistical analyses were performed with PASW v.18 (IBM SPSS statistics, IBM Corporation, Somers, NY).

3. Results

The mean (SD) optimal cut-off frequencies for all force and moment variables were greater for the fracture trials (605.8

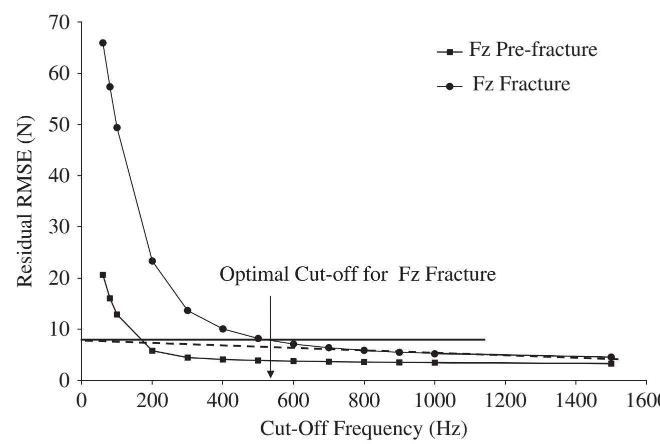

Fig. 2. Typical, axial force (*Fz*) results of the residual analysis comparing a pre-fracture and fracture trial for a selected specimen. Also shown on the *Fz* fracture curve is the method of determining the location of the optimal cut-off frequency. The optimal cut-off is determined by drawing a straight line (dashed line) from the linear portion of the RMSE–frequency curve to the *y*-axis intercept. A second line (solid line) is drawn parallel to the *x*-axis from the intercept to the RMSE–frequency curve. The optimal cut-off frequency is that which corresponds to the intersection point on the curve (shown here by the arrow; Winter, 2005).

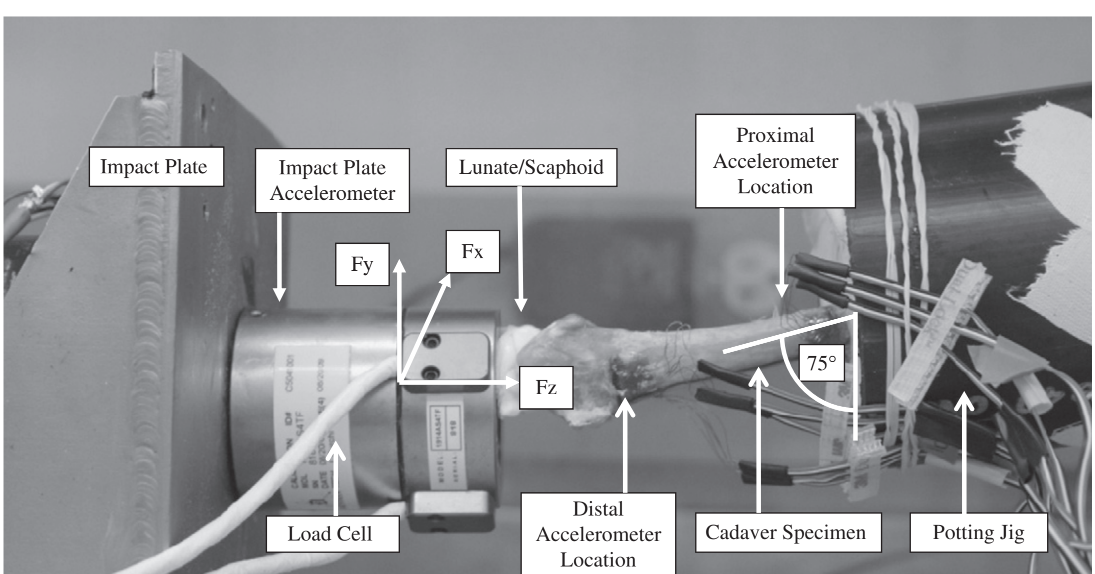

Fig. 1. Experimental set-up for the cadaver radius specimens in the pneumatic impactor. *Fx*, *Fy*, and *Fz* are in the medial–lateral, superior–inferior, and anterior–posterior directions, respectively. Note that the accelerometers are not actually included in the current diagram.