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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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