Study of Phalangeal Fracture Threshold and Design of a Surrogate for Human Finger

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Introduction: Fractures of phalanx caused by industrial accidents are one of the most disabling fractures in the hand [1]. Except a limited number of studies which focus on pinch injury induced by car power windows [2], no detailed injury threshold has been reported. Furthermore, there was no hand surrogate to represent the human finger to evaluate the efficacy of protective wears, e.g. gloves. A series of tests was conducted to study the ultimate force using human cadavers. Results showed that the peak force is a good predictor for the risk of fracture. A brass surrogate similar to a finger was designed to measure the strain and impact force. The performance was verified and ready for future use in evaluating protective gloves.

Methods: Quasi-static tests (0.5 mm/s) were conducted using an Instron testing system while dynamic drop tests (1-2 m/s) were used to evaluate the dynamic responses. For both tests, the impactor was a steel cylinder with a diameter of 25.4 mm to mimic typical loading configuration in accidents (e.g. oil pipe hit). The Instron machine reported impact force and displacement in quasi-static tests. In drop test, guide wires were used to make the load vertical and perpendicular to the finger segments, and two accelerometers and one load cell were used to measure the impact force. Fracture of a bone was identified by a sudden drop of the force-time curve and confirmed by X-ray imaging and autopsy.

Two male and two female cadaver hands were tested using the Instron machine in order to compare the maximum peak force at fracture and force-deflection patterns due to quasi-static loading. Middle and proximal segments of each finger were tested one segment at a time. Additionally, drop tests on respective male and female cadaver hands were conducted in order to better understand bone bending and damage as well as observe the maximum peak force when impacted from different heights varied from 3 to 7 inches. After careful examination of the force history, if no fracture was found, the drop height was then raised and the experiment was repeated.

A finger surrogate made of a brass tube of similar diameter of a human finger was designed to measure the impact force observed at finger. This finger surrogate represented the proximal segment of a middle finger. A brass ring is attached in each end to represent the proximal and distal knuckle respectively. One strain gauge was bonded at the bottom to measure the bending, each of four shear gauges was attached at 45° angle to measure shear deformation near each of the ring, and one gauge was glued on the ring to measure the compression (Fig. 1). Similar Instron and drop tests previously described were conducted on the surrogate. Parameters recorded were the peak force and outputs of 6 strain gauges. The force and surrogate strain time histories were recorded during the tests on human finger segments and the surrogate for comparison. Autopsies were conducted at the end of all test series.

Results: The injured fingers showed multiple fracture types including mid-shaft transverse, condylar oblique and condylar transverse fractures, in accord with [3]. A number of fractures were not detectable through palpation or X-Ray, but could be found at autopsy. Male fingers had a significantly higher fracture threshold compared to females (Fig. 2). Also, injury thresholds were higher in dynamic drop tests compared to quasi-static tests, due to rate dependency of bony material. Based on the two male
samples (of average size and age of physical workers), we found the dynamic threshold of peak force is 1542 N for male fingers, by grouping drop tests of both males. Good linear correlation can be found (R-square = 0.910) between impact forces and shear strain readings, showing low sensitivity of hitting position in between two rings of surrogate. The measurements of bending or compressive strain were more suitable for some specific loading positions. The peak forces and shear strains were lower when the surrogate was protected by a glove. Subsequently, the brass surrogate was calibrated based on shear gauges to measure the impact force and evaluate the potential injury threshold.

**Discussion:** Because females generally have smaller hands and the two female specimens were of advanced ages, results could have exaggerated gender difference more than expected. One must also consider that different finger segments have different fracture thresholds, so it is understandable that failure patterns and thresholds are different. Force and shear strain have a linear relationship and thus, may be an acceptable parameter to understand and predict phalangeal injury or fracture. The brass surrogate is as stiff as the hardest finger segments as shown in Fig. 3, but it was intentionally designed this way so that it can be reused for glove evaluations. Industrial gloves afford the finger to take a higher impact energy compared to bare finger but different designs of these gloves called for a surrogate to evaluate the efficacy of these gloves reliably and repeatable. It is believed that using the force threshold from cadaver tests and the surrogate is a good method when evaluating the finger protection performance.

**Significance:** The study reported new cadaver tests on human figures and proposed ultimate force threshold for prediction of finger fractures under compressive loading from dorsal direction. A finger surrogate was designed for evaluation of efficacy of finger protection. The force measurement from strain gauges was validated for glove mechanical performance evaluation in future.

![Peak Force Comparison](image)

*Fig. 2 Peak forces of 4 subjects in both low speed and high speed impacts*
Fig. 3 Comparison of force deflection curves between brass surrogate and human fingers.

Fig. 1 Brass surrogate with strain gauges installed

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