From a Real Hand to a Digital Hand: A Transformation for Impact Testing Simulation

Marta M. Moure[1], Josué Aranda-Ruiz[2], Faisal Alessa[3], Eduardo M. Sosa[4]

[1] *Bioengineering and Aerospace Engineering Department, University Carlos III of Madrid, Spain*
[2] *Continuum Mechanics and Structural Analysis Department, University Carlos III of Madrid, Spain*
[3] *Department of Industrial and Management Systems Engineering, West Virginia University*
[4] *Department of Mechanical and Aerospace Engineering, West Virginia University*

ABSTRACT

This work presents the development of a Finite Element Digital Human Hand Model (FE-DHHM) created with several Computer Aided Engineering (CAE) tools. The purpose of the research is to create a simulation model to reproduce the impact of a small-sized and low-mass object on the dorsum of a flattened hand. The digital model includes the complete bone structure, derived from high-resolution laser scanning of human hand bones, and surrounded by soft tissue with material properties representative of a real hand. The simulations include impacts on the fingers, knuckles, and metacarpal region. The impact reaction forces are computed and compared to controlled impact tests performed on synthetic and cadaveric hands. The ultimate objective is to develop a calibrated model that can be used to assess the level of protection offered by metacarpal gloves typically used in different industries.

1. INTRODUCCTION AND MOTIVATION

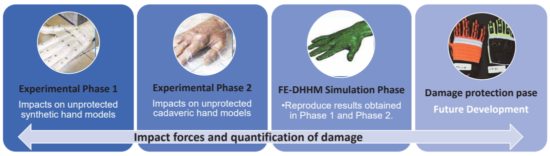
Hand injuries are a significant problem in all industries. Despite the continuous advancements in the technology and the safety procedures for production and maintenance tasks, there are still manual tasks with high-risk factors that can produce hand injuries with varying degrees of severity.

- Just in the mining industry, between 2000 and 2018, there were nearly 42,000 reported accidents involving some part of the hands with different degrees of severity.
- These injuries often yield a functional limitation or disability and may have significant economic implications and loss of productivity.

2. OBJECTIVE

<u>**Main Objective**</u>: Quantify the level of forces resulting of a relatively low-speed impact on the dorsum of a flattened unprotected human hand.

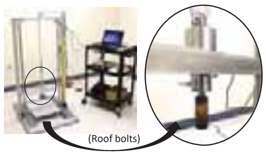
<u>**Ultimate objective**</u>: Develop a calibrated model that can be used to assess the level of protection offered by metacarpal gloves used in different industries.



3. EXPERIMENTAL PHASE

3.1. Impact Testing Machine and Impactors

- Controlled Impacts
- Vertical sliding mass with Hexagonal impactor
- Force plate and load cell connected to the impactors



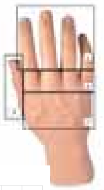
3.2. Surrogate Hands (Synthetic and Cadaveric Hands)

- <u>**Phase 1**</u>: Semi-flexible hand with a 3D-printed bone structure + medical grade ballistic gel for the soft tissue → produces a realistic hand model. (Generation 1 and Generation 2)
- <u>**Phase 2**</u>: Cadaveric hands, specimens provided by the WVU Health Sciences Center, Human Gift Registry, used for validation of models and forces. Testing work recently completed.

Phase 1 – Gen#1 | Phase 1 – Gen#2 | Phase 2

3.3. Impact Zones

Zone 1 – Fingers: Interphalangeal (PIP) joints
Zone 2 – Knuckles: metacarpophalangeal (MCP) joints
Zone 3 – Back of Hand: diaphyseal region of the metacarpals
Zone 4 – Thumb: PIP and MCP joint and first metacarpal



3.4. Material Properties

Human Hand:

- Limited number of studies
- Soft tissues: Ogden and Polynomial Hyperelastic model.
- Bones: $E \in (7{,}000 - 20{,}000)$ MPa
- Bone densities: ρ (0.8 – 2) g/cm^3

Synthetic Hand:

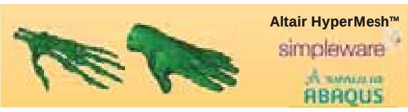
- Soft tissues: medical synthetic gelatin produced by Humimic Medical
- *Work in progress*: Elastic material properties are being determined based on coupon specimens subjected to tensile, compression and shear tests to determine hyperelastic coefficients corresponding to the Polynomial and Ogden forms.

4. SIMULATION PHASE

4.1. Modeling Methodology

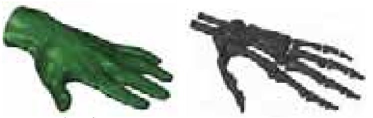
Next Engine® Laser Scanner
- *Set of bones facilitated by WVU HSC*
- *Individual bones scanned with 0.1 mm precision*
- *Surface and STL format files*

CAD Model
- *Soft tissue definition*
- *Assembly and integration with soft tissue*
- *Scaling to 50th percentile*
- *.iges files of bones and flesh*

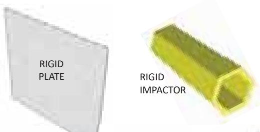


FEA Model
- *Finite element discretization*
- *Materials definition*
- *Loads and boundary conditions*
- *Contact pairs definition*
- *Data visualization*

4.2. FE Digital Human Hand Model – FE-DHHM



SOFT TISSUE (FLESH) ~110K Tetrahedral Solid Elements C3D4 | BONES ~30K Tetrahedral Solid Elements (C3D4)



Problem Definition:
- Abaqus/Standard: Hand positioning on rigid plate (Time: 1 second)
- Abaqus/Explicit : Freefall of the impactor (Time: 0.5 seconds)

FULL MODEL

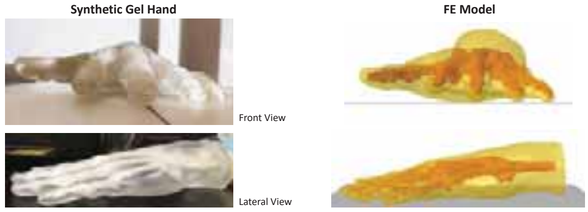
Types of contact interactions:
- Tie for bones and flesh to ensure compatibility of displacements.
- General contact between hand and rigid plate.
- General contact between impactor and hand.

IMPACT MAP

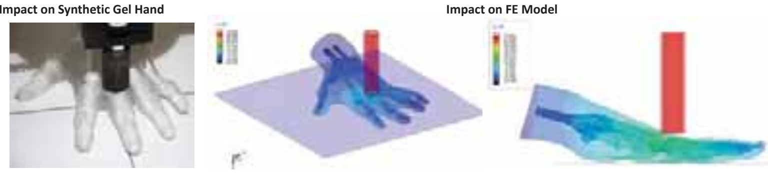
Loads and BCs:
- Hand subjected to self-weight calculated based on bone and flesh densities.
- Impactor with a mass of 5 kg falling by gravity from an elevation of 100 mm.
- Base rigid plate is fixed.
- Impactor can only move vertically.

5. PRELIMINARY RESULTS

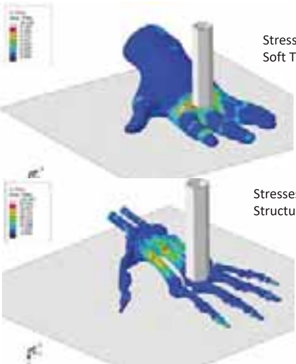
5.1. Hand Pre-Positioning

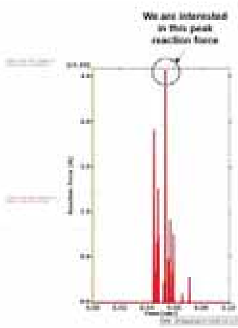


5.2. Vertical Displacement



5.3. Stresses and Peak Reaction Force





Impact Reaction Force Ranges:

Cadaveric Hand 1500 to 2700 N

Synthetic Hand 1800 to 3700 N

FE-DHHM 2600 to 3000 N

OBSERVATIONS

A 3D solid FE-DHHM has been developed to analyze the forces resulting from a localized impact. From the preliminary results, the following observations can be made:

- **The peak reaction force of the FE-DHHM model is in the range of forces measured during the experimental phases with synthetic and cadaveric hands.**
- **The model still requires some fine tuning to better replicate experimental tests.**
- **The prediction of behavior of an unprotected hand provides a baseline for comparison with models that include a protective layer provided by different types and designs of industrial gloves.**

FUTURE STEPS

- **Complete material testing to obtain more accurate coefficients for hyperelastic models corresponding to the actual gel used in the experiments.**
- **Incorporate more geometric details to create a more accurate model (tendons, joints, etc.)**
- **Obtain and adjust material properties of hand's soft tissues to compare with results obtained from experiments with cadaveric hands.**

Acknowledgements

This work was supported in part by:
- **The financial assistance provided by the Arch Coal Inc. Endowment for Mine Health and Safety Research in the Statler College of Engineering and Mineral Resources (CEMR) at West Virginia University.**
- **The financial support provided by University Carlos III of Madrid through the "Aid for the mobility of the own research program".**

E-mail : mmmoure@ing.uc3m.es   Web: http://www.uc3m.es