Experimental Injury Biomechanics of Human Body Upper Extremities: Anatomy, Injury Severity Classification, and Impact Testing Setups

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***Abstract*— Understanding the human body's anatomical aspects helps capture key insights and gather increased information on the underlying human injury mechanisms, injury probability, and tolerance limits. Such knowledge, together with capable robots integrating safety-driven motion planning and control frameworks, enables the development of effective countermeasures for human arm/hand injury in robotics. In this work, thorough treatment for the anatomy, injury types, and severity classifications of human upper body extremities are provided. We also describe various impact testing setups and injury occurrence mechanisms encountered in sports, biomechanics, and forensics literature. The gathered insights provide solid grounds for designing/planning interactive impact setups and robot tasks in a well-informed way regarding the injury biomechanics of the human body upper extremities and their tolerances.**

I. Introduction

In former years, especially in industry, humans couldn't cooperate with robot manipulators closely. That was mainly motivated by the assumed high risk of severe injuries in case a collision between robot and human coworker happens. However, Haddadin et al. [1] showed that this assumption is not valid in general. Physical human-robot interaction (pHRI) is not only possible but rather favorable, and today it is considered the future of industrial robotics. Nevertheless, the robot should not injure a human, which is clearly demanded by the famous three laws of Issac Asimov [2]. This means it is necessary to establish standards for the safety of robotic systems. Such standards must guarantee humans' safety in the vicinity of a robot, but at the same time, should not shrink the robot productivity unnecessarily. Therefore, it is crucial to adequately understand the human injury biomechanics in order to determine the reasonable limits to be enforced. Integrating such human injury data into the robot controllers can be finally achieved with, for example, the safe motion unit (SMU) concept proposed in [3] through online computations of the so-called reflected mass [4].

For building up a more fundamental knowledge base about the injury biomechanics of the human body upper extremities, an extensive literature review process was completed. Due to space limitations and to focus more on highlighting the critical information, only a concise summary is provided. This work focuses on injuries for human hand and arm exclusively, opposed to e. g. skin that covers the whole body. This leads to mostly bone related injuries, as e. g. fractures, which represent a worst-case scenario seen from robotics perspective. Nevertheless, the knowledge of upper limits is important to precisely focus further discussions in the robotics domain.

A. Related Work

An introduction with anthropometric data for the human arm and hand is given in [5]. A more detailed description of the structure and interaction of the different parts, like bones and muscles, is introduced in [6]. An excellent overview of fracture biomechanics is given in [7], whereas the standard classification scheme, the AO/OTA[1] classification of fractures and dislocations is introduced in [8] and further extended in [9]. Furthermore, to classify the severity of injuries commonly the Abbreviated Injury Scale (AIS) [10], [11] is used.

Concerning the efforts to determine humans' tolerance thresholds, the available published work is rather old, see e. g. [12] and [13]. In both works, generic data for the fracture tolerance of human long bones was collected, which can still be used today. Such data for the arm's long bones were also collected in more recent years by many researchers, e. g. [14]–[25]. Among these, especially the work in [15], [18], [21] is very relevant also to robotics. For generic hand injury data, only the work in [26] is available up to the authors' knowledge. In recent years, more specific data-sets for special proposes are being generated. For example, the material properties of bones are investigated in [27]–[30], where valuable biomechanical information is provided. To evaluate the correctness of Finite Element Modeling (FEM) simulation methods several studies were conducted, e. g. [31]–[34]. However, a low number of specimens were usually used, and the resulting values are not always published.

Falling of humans on their outstretched hands, especially in Sports, is investigated intensively. A lot of research is conducted in determining the influences on human falls, like surface stiffness [35], elbow flexion [36] or fall arrest strategies [37], [38]. Valuable related data is provided by experiments evaluating the forces [39] and pressure distribution [40] on the hand. A controversially discussed issue is the efficiency of wrist protectors in sports like skating or snowboarding. A very good review on this issue is provided by [41], with the main important references [42]–[48]. An extensive measurement series with human volunteers is conducted for evaluating falls during snowboarding in [49], whereas several relevant standards (such as e. g. the DIN EN 14120:2007 [50]) were used to compare different protective

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[1] AO stands (in German) for "Arbeitsgemeinschaft für Osteosynthesefragen" that can be roughly translated (in English) to "W

devices. General results in injury biomechanics of upper extremities in automotive accidents are presented in [51] and [52]. Injuries to the extremities are historically considered not life-threatening, so they were sometimes neglected in automotive safety studies, see e. g. [53] for a recent example. From the year 1990 and on-wards, intense research has been conducted to determine the injury patterns and tolerance of upper extremities in car accidents. Of special interest was the interaction of airbags with the extremities, which leads to the term of *airbag aggressivity* [54]. Additionally, this topic was extensively investigated by [55]–[60] and usable data-sets are provided in [61]–[63]. Another issue was the development of dummies with a higher human fidelity of the extremities [57], [64], [65], with the experimental data-sets mostly lacking. Moreover, there is also considerable quite general data provided in [66]–[71]. Based on data from all these listed sources, Duma et al. developed the concept of risk functions [72], [73]. Another injury pattern related to the automotive industry is jamming fingers in a closing automatic car window. A good overview on this topic is provided in [74], with key references to [75]–[78]. A similar case is clamping in machinery, whereas safety thresholds are given in norms, e. g. [79]. Even though many experimental studies have been conducted in injury biomechanics literature for the human upper exterminates, experimental data-sets are often not provided, and still comprehensive related reviews usable for the robotics research community are lacking.

B. *Problem definition and contribution*

To develop safe pHRI enabled robots, one needs to understand the essential anatomical descriptions and possible types of human injuries upon (un-)intentional collision incidents. However, in robotics, such biomechanics knowledge for the human body upper extremities is largely missing. Therefore, our main research contributions to bridge this knowledge gap are to

- provide a concise treatment for anatomical and motion descriptions of the human body upper extremities,
- introduce their possible injuries together with detailing how to classify their severities, with a focus on worst-case scenarios, and
- present their encountered impact testing setups in the reviewed biomechanics literature.

II. Anatomical and Motion Descriptions

An adequate understanding of the human upper extremities' underlying anatomy is necessary to understand the related medical terminologies and descriptions of injury types and mechanisms. For more detailed anatomical treatment, one can consult a more specialized book, e. g. [5], [7]. The human upper extremities consist of the shoulder, the arm, the forearm, and the hand, as shown in Fig. 1. The length and masses of these body parts are summarized in Tab. I.

The shoulder joint links the arm to the torso and is built of the clavicula and the scapula. It offers many degrees of freedom, so rotations around all three anatomical axes and translations in up-down and forward-backward directions are possible. It is not further investigated since it is not endangered to injury in close human-robot cooperation. The

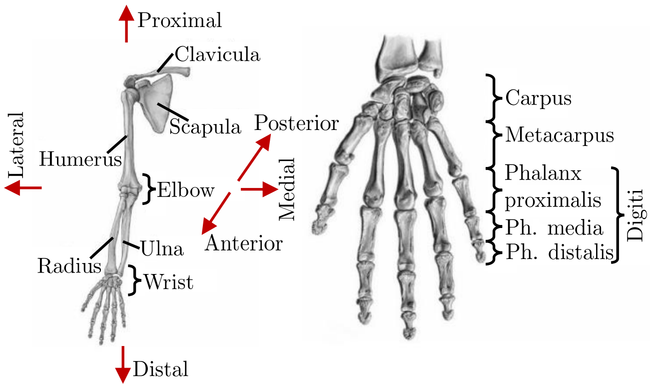

Fig. 1: Directions and skeletal structure of the human upper body extremities [5], [7].

Body part	Value	Male (%)			Female (%)		
		5th	50th	95th	5th	50th	95th
Upper arm	length [m]	0.333	0.361	0.389	0.306	0.332	0.358
Lower arm (including hand)	length [m]	0.451	0.483	0.517	0.396	0.428	0.458
Upper arm	mass [kg]	1.84	2.23	2.67	1.41	1.71	2.07
Lower arm	mass [kg]	1.14	1.39	1.66	0.84	1.02	1.24
Hand	mass [kg]	0.43	0.52	0.63	0.34	0.42	0.50

TABLE I: Anthropometric measurements of the human upper arm and lower arm (including the outstretched hand), adapted from [5].

long bone in the upper arm is called the humerus, and in the forearm there are radius and ulna. These are linked together with the elbow joint. Movements of the forearm towards the humerus are called flexion, and the other direction is named extension of the forearm. The wrist joint, also called carpus, connects the forearm and the hand. It allows many degrees of freedom, e. g. in combination with the ulna, to rotate the hand. This motion's two directions are called pronation, which means the palm is facing downward, and supination, which means the palm is pointing upward. Another motion is pulling the back of the hand upwards what is called dorsiflexion, and downward is called plantarflexion. The first one occurs, for example, as a protection reaction while a human is falling on the outstretched hands. The human hand consists of the metacarpus bones, that are directly attached to the wrist, and the digiti bones, which build the fingers, see also Fig. 1 (right) and [6]. These three bones are the proximal phalanx (PP), middle phalanx (MP), and distal phalanx (DP), from the palm to the tip. The respective joints are called the metacarpophalangeal joints (MCP), which are connecting the fingers to the hand, the proximal interphalangeal joints (PIP), and distal interphalangeal joints (DIP).

III. Possible Injuries and their Classification

1) Fractures: Whether a fracture occurs during a collision or accident is dependent on a lot of factors. There are external influences, such as the applied forces or the impactor geometry, but also medical influences, like the Bone Mineral Content (BMC) or the shape of the bone. The latter influences are investigated in various medical publications, e. g. [6], [27]–[30]. In general, one can conclude that the BMC has a strong influence on fractures. However, apart from osteoporosis, this BMC value decreases with the increasing age of the people [6]. Furthermore, there are differences between female and male bones [6], which again influences how fractures occur. The bones of women are smaller in general, and therefore the bone strength is reduced. The decrease of BMC is higher, and differences in female bones' cross-sectional geometry result in weaker bones. Therefore, some studies e. g. [62], [67], [71] focus on female specimen to generate a lower tolerance border.

Some typical fracture patterns are occurring under certain circumstances. A so-called "nightstick" fracture [7] is a diaphyseal ulna fracture without a radius fracture. This fracture can happen with low-energy direct impacts, e. g. an inflating airbag. So, this fracture pattern might also result in blunt impacts on the forearm. Resulting from a fall on the outstretched hand a Colles fracture is prevalent. It describes a distal radius fracture. This pattern is seen frequently in sports injuries, e. g. in snowboarding it is the most often reported injury [41]. Another reason for such injury is the impact on the palm while holding them in a defensive pose. So the wrist joint is in dorsiflexion, and an impactor is hitting the palm of hands frontally. Hands and fingers are injured quite often in our daily life activities since they are extensively used. However, their injury biomechanics are rarely investigated. This might be due to the enormous variety of possible injury patterns. One common pattern is the jamming fingers in a closing car window, which is examined in several studies [74]–[78]. The focus there was on determining a reasonable closing force threshold so that no injuries occur. The current threshold used by automotive industry is 100 N [74]. Another injury pattern is clamping in machinery, especially at presses or stamping machines. For these a maximum force threshold of 150 N is given if no other safety measures (e. g. covering) are available [79].

2) Other injuries: Despite that fractures are treated extensively in the literature, there are many other possible injuries. The soft tissues surrounding the bones, like skin and muscles, are prone to be injured. However, these are not exclusive injuries for the arms or hands since the soft tissues cover the whole body. Furthermore, human tolerance for pain is also not examined due to the same reason. The latter might also be used to generate a lower border for forces a robot could exert on humans without any harm.

3) Injury severity indices: One common injury severity index is the Abbreviated Injury Scale (AIS) [10], [11]. It was originally developed by the automotive community to assess the fatality of accidental trauma. This index classifies single injuries according to their survivability, see Tab. II. In the AIS classification code format, the first digit is the body region (e. g. 7 for upper extremities), and the second encodes which specific part is injured (e. g. 5 for skeletal). The remaining four numbers specify a particular injury, but there is no severity ranking. The actual severity index, as listed in Tab. II, is finally added at the end with a dot in between. Since this index originated from vehicle crashes (mostly having severe injury patterns), it is therefore not precise in describing hand or arm injuries. These are mostly classified as AIS1 or AIS2, whereas for AIS3 the whole hand or arm would be lost. Thus, higher severity cannot be reached. Several extensions of this index to describe multiple injuries also exist, e. g. the Injury Severity Score (ISS) or the maximum AIS (mAIS).

AIS score	Injury severity	Examples for upper extremities
0	non-injured	
1	minor	Minor superficial abrasion or laceration of skin; digit sprain
2	moderate	Major abrasion or laceration of skin; finger crush/amputation
3	serious	hand or arm crush/amputation
4	severe	
5	critical	
6	untreatable	

TABLE II: The Abbreviated Injury Scale (AIS) severity index [11].

Fractures of long bones can be classified according to the AO/OTA [8], [9]. The labeling scheme is BS-TG.S_g, where B is the number of a bone, S specifies the segment of a bone, T denotes the type of a fracture (letters "A", "B" or "C" allowed), G and S_g provides the group and subgroup of a fracture. From the anatomic location, only bone 1 (humerus) and 2 (ulna and radius, regarded as one bone in this classification) are investigated. These bones are separated into three segments, the proximal (1), the diaphyseal (2), and the distal (3) segment. The following morphology code then gives a more detailed description of the fracture. The three types (for the diaphyseal segment) are simple (A), wedge (B), and complex (C). The groups further distinguish between fractures e. g. spiral (A1) or multifragmentary (B3). Besides, this classification can also be extended to hand bone fractures [9], but this is not standardized as for the long bones. The original classification is meant for labeling fractures, but it could be seen as a severity index too [51]. The reason is that higher numbers and letters label more severe injuries. However, this is only an indicator and not a well-ordered ranking system.

IV. Testing setups and findings

Historically, lots of crash-tests had been executed to evaluate the biomechanical injury tolerance thresholds of the human body upper extremities. The experimental setups and issues related to different impact testing methods are described in the following. Due to the apparent limiting safety regulations and ethical restrictions for human volunteer testing, most experiments are usually done with cadaver specimens. The test subject can then be impacted till fractures occur. Only few experiments were done with alive human volunteers to determine tighter tolerance levels for mild injury or pain thresholds.

A. Impact tests with cadaver specimens

Experiments with upper extremities of cadaver specimens focus mostly on a specific arm/hand bone or a particular region. Therefore interactions of different subject body parts are not seen. Furthermore, the effects of muscles and skin are neglected, since it is dead material or even removed, e. g. [13]. There is also a difference in the behavior of embalmed and fresh specimens [19]. In the reviewed biomechanics literature, mostly fresh or fresh-thawed specimens were used, except in [21].

One common method to test bones' mechanical properties is to use a material testing machine (MTM). These machines apply a well defined increasing force on a specimen till

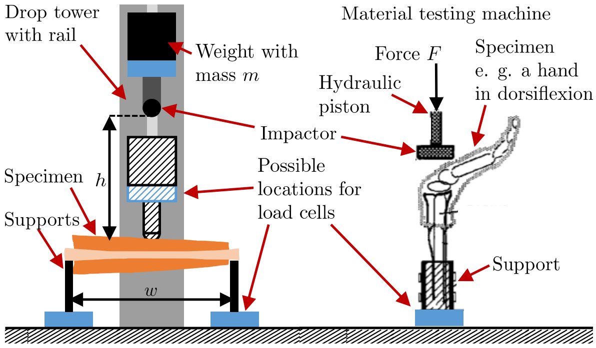

Fig. 2: A schematic sketch for the drop tower (DT) test setups (left) and material testing machine (MTM) setups (right) as adapted from [28]. The support arrangement for long bones (DT setup) and for the wrist in dorsiflexion (MTM setup) are also shown.

fractures occur. This is done by clamping the specimen with a hydraulic piston, see Fig. 2, right. The piston speed is mostly rather low and, therefore, these experiments are considered to be static or quasi-static. The velocity ranges mostly from 0 to $0.2\,\mathrm{m/s}$, except at [68] and [70] are $3.3\,\mathrm{m/s}$ and $7.6\,\mathrm{m/s}$ used. In experiments with drop towers (DTs) the force is generated by dropping a weight from a certain height onto the specimen, see Fig. 2, left. Consequently, the velocity is higher, and these experiments result in more dynamic impacts. The impactor weight ranges from $2.5\,\mathrm{kg}$ to $23\,\mathrm{kg}$ and the used impact velocity is between $2\,\mathrm{m/s}$ and $4.5\,\mathrm{m/s}$. In nearly all experiments, the impactor force is measured directly at the impactor or the supports. For DT setups, load cells or force plates are usually used. Some of the MTMs measure the exerted force by themselves. As in all experiments, the bones are tested till fracture, and only the highest peak values of the forces right before the fracture occurs are used to compare the results. In several experimental setups, the bending moment M is reported additionally, and in [67], it is the only measured value.

For the long bones, mainly three-point bending tests were conducted. This means the bone is laying on two supports at the bone ends while the force is applied in the middle of the bone. If the bone is fixed at the ends, this negatively influences the test results [69]. Most experiments kept a fixed width between the supports. However, already in [13], it was concluded that the total length of the bones varies between different humans and, hence, the authors argued that the support width should reflect this. The impactor geometry was mostly a sphere or cylinder with $\sim 25\,\mathrm{mm}$ diameter. In [65] and [15] a flat impactor was used, whereas an edge shaped impactor was used in [13].

To determine a threshold for a Colles fracture while a fall on the hands, there are many experiments carried out with wrists in dorsiflexion, see Fig. 2, right. Several of these tests tried to evaluate the effect of wrist protectors for skating or snowboarding. Unfortunately, there was no common standard for testing this equipment, so the studies are difficult to compare [7]. Another reason for this difficulty is the use of different dorsiflexion angles and significant variations of the resulting effective impact mass, highly dependent on the flexion angle of the elbow [37]. The reported values for the effective mass ranges from $3\,\mathrm{kg}$ to $23\,\mathrm{kg}$ [7]. The used

Arm/hand Part	Setup	Ref.	Impactor Primitive
Finger		[77]	Car window
Finger		[74]	Car window
Wrist	All	[49]	Flat
Wrist	FL	[39]	Flat
Wrist	FL	[35]	Flat
Wrist	FL	[40]	Flat
Wrist	FM	[37]	
Wrist	Real	[48]	

TABLE III: Parameters of all reviewed experimental setups for volunteers testing. Setup FL and ML means forward falls in the "low" and "middle" arrangements, all with low starting height while kneeling on the floor, whereas in the latter case the subject body was completely lifted.

impactors were flat, or the test was done by crashing the wrist against a surface. In one study [73] (also originated from the automotive industry), a car door hand-grip is used as an impactor. Up to the authors' knowledge, the work of Carpanen et al. [26] is the only biomechanics source for general biomechanical data for the hand. Their test hand specimen was laying on a surface, and a weight of $2.5\,\mathrm{kg}$ was dropped on its back. A cylindrical impactor with $12.5\,\mathrm{mm}$ radius was used. The impact velocity is increased from $1.98\,\mathrm{m/s}$ over $3.13\,\mathrm{m/s}$ to $4.08\,\mathrm{m/s}$, if no injury has occurred at the lower levels. Regarding the fingers, the automotive industry was interested in determining a threshold for a not dangerous closing force for automatic car windows. Hence, some experiments were done with a setup similar to jamming the fingers in a car window, e. g. in [74]. Their test impactor was a car window shaped edge, and its velocity was roughly quasi-static.

B. *Impact tests with volunteers*

By employing volunteers as subjects in the impact experiments the results are more realistic, since all parts of the human body are active and interact with each other, in contrast to cadaver specimens. However, there are highly restrictive standards concerning safety for experimenting with volunteers, and no injury should happen. So these results mark the region in which an accident is completely hazard-free. In nearly all the experiments only the force was measured since this is rather easy with e. g. force plates. The evaluated data were the highest values of the first peak after the impact. The mean of these peak values from different experiments is then used to compare the results. In [40], the pressure distribution of the palm while the impact was recorded, and the mean peak force is also calculated for comparability. See also Tab. III for details.

To investigate the mechanics of the common Colles fracture in sports, experiments were done with human volunteers falling on their hands. Several different arrangements were used. One crucial distinction is the start position or pose of the human. Most experiments can be grouped in the setups described by [49]. Start position "low" means the human is kneeling on the floor, which results in only the upper body falling on the hands. Position "middle" means the whole body is lifted with a crane, but the drop height is rather low. Start position "high" means falling from standing upright. In the latter arrangement, injuries are likely to occur, and therefore athletic crash mats are used. In [49] the drop height could be chosen by the volunteers, and therefore it varies. The experiments in [35], [39], [40] were all done with a "low" setup with drop height between $1-5\mathrm{cm}$. The setup in [37] is more related to the "middle" setup with a drop "height" of $5\,\mathrm{cm}$. Another important aspect of falling humans is the angle of the elbow. In [37], this influence was investigated with volunteer fall tests, with different elbow flexion angle. Due to high forces occurring with the stiff elbow, a damping foam was also used. Nevertheless, the recorded forces strongly depend on the elbow angle. In [35] and [40] the participants were advised to use a stiff elbow. In contrast, in [49] and [39], no advice was given. Hence, a natural falling behavior could be assumed. The most realistic values of humans falling are presented in [48]. They used an instrumented glove and recorded the forces while real snowboarding. So there is no classification of the setup possible.

Regarding the finger jamming in a closing car window, two different arrangements were used. In [77], a realistic setup with a modified car door was used. The participants exerted the closing force on their fingers by themselves till their maximal pain tolerance was reached. Using an artificial setup the force could be exerted to a particular bone or joint as in e. g. [74]. The shape of the impactor is again like the car window edge.

V. Conclusions

In this paper, the quantitative results of our extensive literature review process on the injury biomechanics on the human body upper extremities are summarized. The gathered knowledge extends our unified framework of data-driven safety in robotics. However, in this review the lack of literature relevant to robotics is apparent. Nevertheless, this rich knowledge base can be treated as guideline for designing crash-testing experiments in robotics to systematically generate relevant impact data-sets, for example, as described in e. g. [80].

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