Craniofacial Injuries for Helmeted and Unhelmeted Bicyclists in Germany

Shiyang Meng, Fritjof Gidion, Nils Lubbe

Abstract Current bicycle helmet standards require impact testing mostly covering cranial or skull vault. Bicyclists are exposed to impacts to the face causing facial and basilar skull fractures, and soft tissue injuries, in addition to traumatic brain injuries. We aim to describe patterns and frequencies of craniofacial injuries grouped by anatomical and injury sites to inform new test method development in future bicycle helmet standards and subsequently promote protective designs. We analysed fully reconstructed crashes involving a bicycle from the German In-Depth Accident Study (GIDAS), crash years 2010-2022. The type and location of an injury was determined through the Abbreviated Injury Scale (2015 version), a GIDAS-own variable, and free-text information. We found that a substantial portion of craniofacial injuries were to the face for both helmeted and unhelmeted bicyclists. Facial injuries shifted from the upper face to the mid- and lower face when a helmet was worn. We identified the mid-face as the most prominent region for improving bicycle helmet safety. Hence, a new test method with an extended test area covering mid- and lower face is recommended and injury risk to commonly fractured facial bones should be assessed in future standards. Protective designs appear technically feasible: A visor in connection with a chin guard, or novel concepts using inflatable technology, can improve bicycle helmet designs for facial impact protection and could be assessed in future standards.

Keywords Basilar skull fracture, bicycle, facial fracture, head, helmet, soft tissue injury.

I. INTRODUCTION

Current safety standards for bicycle helmets around the world require an impact test area that covers only the skull vault, including EN 1078 (Europe), CPSC 16 CFR 1203 (United States), JIS T 8134 (Japan), AS/NZS 2063 (Australia and New Zealand) and GB 24429 (China). Fig. 1 shows the location of test lines, above which impact tests are conducted, as defined in EN 1078 and CPSC on a featureless EN 960 headform. The headform is overlayed with the statistical mean head shape [1] illustrating external landmarks on the head and face. The distance between sellion (located at the deepest depression of the nasal bones) and the standards' test line on the forehead measures approximately 56 mm. Thereby, the standard test line is around 10 mm below the hairline for most Caucasian males and females [2]. This leaves the question whether current helmet standards ensure helmet safety design and protection against impacts outside the standards' test area that may occur in the real world, particularly for impacts to the face.

Impacts to the face can transfer blunt forces causing facial injuries which also increase the risk of traumatic brain injury among bicyclists [3]. Facial injuries by themselves are seldom life-threating but are often associated with severe morbidity, disfigurement, impairment of vision, and psychological problems [4]. Field studies show that while helmets reduce facial injuries overall, the amount of protection varies with locations on the face [5-6]. The level of protection for reducing facial soft tissue injuries and fractures decreases from upper face to mid and lower face, essentially depending on the proximity to the rim of the helmet [6]. Improved helmet design offering facial protection has been called for [6–10]. In the past few decades, numerous studies have focused on helmet assessments to prevent traumatic brain injuries resulting from a linear or oblique impact to the skull vault, while little effort has been directed to bicycle helmet assessment to prevent facial fractures and basilar skull fractures.

To guide helmet design and assess facial impact protection, a new evidence-based test method needs to be included in future bicycle helmet standards. Real-world crash data can inform the development of test methods to answer questions like where to test and which injury or injuries the assessment should target. Previous studies have often coarsely defined facial injuries within three regions, (i.e., upper, middle, and lower face) [5-6] or

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aggregated injuries from both helmeted and unhelmeted bicyclists [11], which makes it difficult to identify protection priority for targeted populations and propose helmet design improvements. Therefore, we aim to describe patterns and frequencies of craniofacial injuries grouped by anatomical and injury sites for both helmeted and unhelmeted bicyclists.

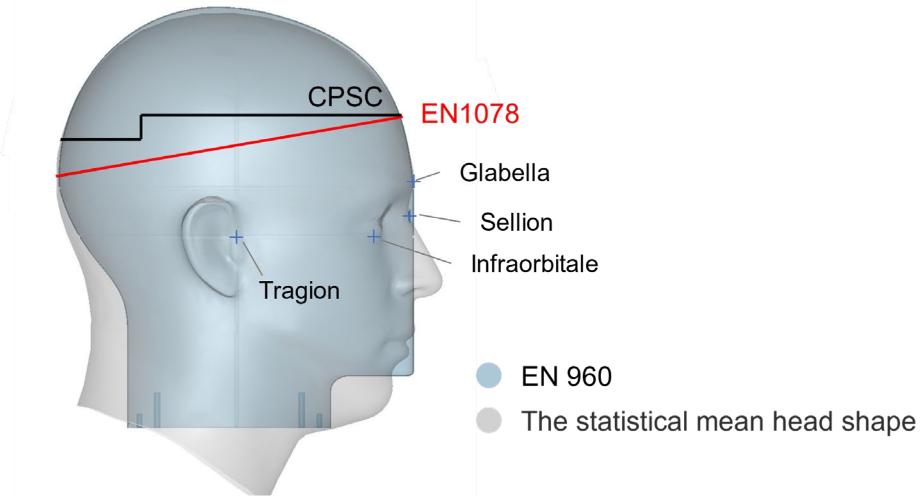

Fig. 1. Location of test lines defined in EN 1078 and CPSC on a EN 960 headform (head circumference 575 mm). The statistical mean head shape [1] (head circumference 575 mm and breadth-to-length ratio 0.77), downloaded from http://humanshape.org/head/, was overlayed on the EN 960 headform after aligning the Frankfurt plane (connecting infraorbitale and tragion) with the basic plane of the headform. Surface landmarks (+) are shown on head and face of the statistical mean head shape.

II. METHODS

We analysed fully reconstructed crashes involving a bicycle from the German In-Depth Accident Study (GIDAS), crash years 2010-2022. These included 1,519 helmeted bicyclists and 5,327 unhelmeted bicyclists, excluding pillion riders and run-over cases. External soft tissue injuries (e.g., skin avulsion) and skeletal fractures (e.g., basilar skull fracture) to head and face were investigated. To be included, the injury must have been coded as either the body region *face* or *head* according to the 2015 version of the Abbreviated Injury Scale (AIS) codebook [12], and all severities ranging from 1 to 6 (minor, moderate, serious, severe, critical, and maximum) were considered.

The location of an injury was determined through three variables successively: the injury codes from the AIS 2015 codebook, the GIDAS-own variable *SITZ* describing the location of an injury, and *DIAGNOSE*, which is a free text variable for injury type and location. Each of these variables will show a value in the GIDAS injury records but the extent and quality of the information can vary depending on the type of injury and the information available to the analyst reconstructing the case. It can therefore be beneficial to gather all information from the three variables for an individual injury to extract the desired information. In the few cases where information from these variables was conflicting, we manually checked supplementary materials in the case files, e.g., hospital records, or classified the injury as not locatable. Injuries that were not further specified with location information were also classified as not locatable. Finally, we mapped soft tissue injuries to 11 esthetic units, (i.e., forehead, eyes, nose, cheeks, lips, ears, chin, frontal, parietal, temporal and occipital) and fractures to 12 bone segments (i.e., orbita, nasal, zygomatic, maxilla, mandible, frontal, parietal, temporal, occipital, anterior, middle, and posterior portion of the skull base) of the head and face. The anterior portion of the skull base consisted of frontal, sphenoid and ethmoid bones.

III. RESULTS

The query resulted in 731 soft tissue injuries and 74 fractures for helmeted bicyclists, and 3,115 soft tissue injuries and 477 fractures for unhelmeted bicyclists (Table I and II). Facial injury accounted for 64.8% of all soft tissue injuries and 67.3% of all fractures for unhelmeted bicyclists, while it accounted for 83.4% of all soft tissue injuries and 86.5% of all fractures for helmeted bicyclists. For unhelmeted bicyclists, 76.0% of soft tissue injuries and 90.6% of fractures were located, and 79.6% of soft tissue injuries and 93.2% of fractures were located for helmeted bicyclists.

A frequency distribution of soft tissue injuries for helmeted and unhelmeted bicyclists is shown in Fig. 2, facial fractures are shown in Fig 3. Due to a limited number of skull fractures for helmeted bicyclists, i.e., 5 skull vault fractures (4 located) and 5 skull base fractures (2 located), a frequency distribution of skull fractures is only shown for unhelmeted bicyclists in Fig 4. Considering soft tissues, the most frequent facial injuries shifted from the forehead (33.3%) for unhelmeted bicyclists to the cheeks (18.6%) for helmeted bicyclists (closely followed by chin/lips, 17.8%). The most frequent soft tissue injury to the head/scalp shifted from occipital (45.4%) for unhelmeted bicyclists to frontal (38.6%) for helmeted bicyclists. Considering skeletal injuries, nasal fractures were most frequent for both unhelmeted and helmeted bicyclists, representing 38.2% and 31.7% of all fractures, respectively. The second most frequently fractured site shifted from orbita (25.9%) for unhelmeted bicyclists to maxilla (23.8%) for helmeted bicyclists. Only unhelmeted bicyclists sustained a substantial amount of skull injuries. Basilar skull fractures occurred mostly (90.7%) at anterior and middle fossa while skull vault fractures were mostly located at the frontal bone (36.0%) followed by the temporal bone (26.0%).

TABLE I

PROPORTION* OF EXTERNAL SOFT TISSUE INJURIES ON HEAD AND FACE FOR HELMETED AND UNHELMETED BICYCLISTS

		Unhelmeted	Helmeted
Face	Located	1792 (57.5%)	538 (73.6%)
	Not Located	226 (7.3%)	72 (9.8%)
	Combined	2018 (64.8%)	610 (83.4%)
Head	Located	577 (18.5%)	44 (6.0%)
	Not Located	520 (16.7%)	77 (10.5%)
	Combined	1097 (35.2%)	121 (16.5%)
Total		3115	731

* Some percentages do not add up to 100 due to rounding. Case counts are accurate.

TABLE II

PROPORTION* OF FACIAL AND SKULL FRACTURES FOR HELMETED AND UNHELMETED BICYCLISTS

		Unhelmeted	Helmeted
Face	Located	317 (66.5%)	63 (85.1%)
	Not Located	4 (0.8%)	1 (1.4%)
	Combined	321 (67.3%)	64 (86.5%)
Vault	Located	50 (10.5%)	4 (5.4%)
	Not Located	23 (4.8%)	1 (1.4%)
	Combined	73 (15.3%)	5 (6.8%)
Base	Located	65 (13.6%)	2 (2.7%)
	Not Located	18 (3.8%)	3 (4.1%)
	Combined	83 (17.4%)	5 (6.8%)
Total		477	74

* Some percentages do not add up to 100 due to rounding. Case counts are accurate.

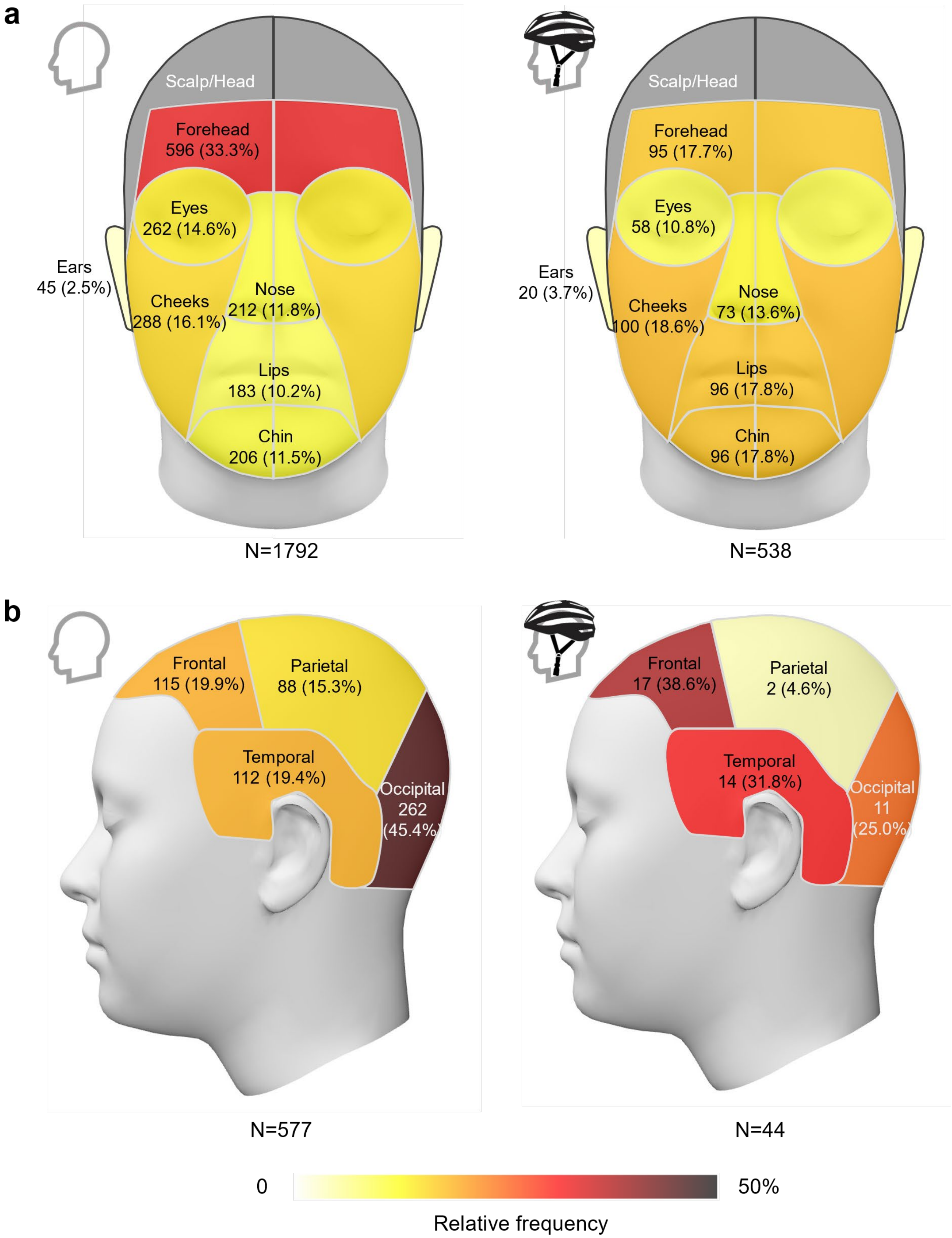

Fig. 2. Frequency distribution of soft tissue injuries on (a) face and (b) head for helmeted (right) and unhelmeted (left) bicyclists. Injury frequency is expressed in *absolute frequency (relative frequency).* Each injury location on the face or head is colour-coded with a continuous colour scale, determined by its relative frequency. The colour scale is ranged from 0 (minimum) to 50% (maximum).

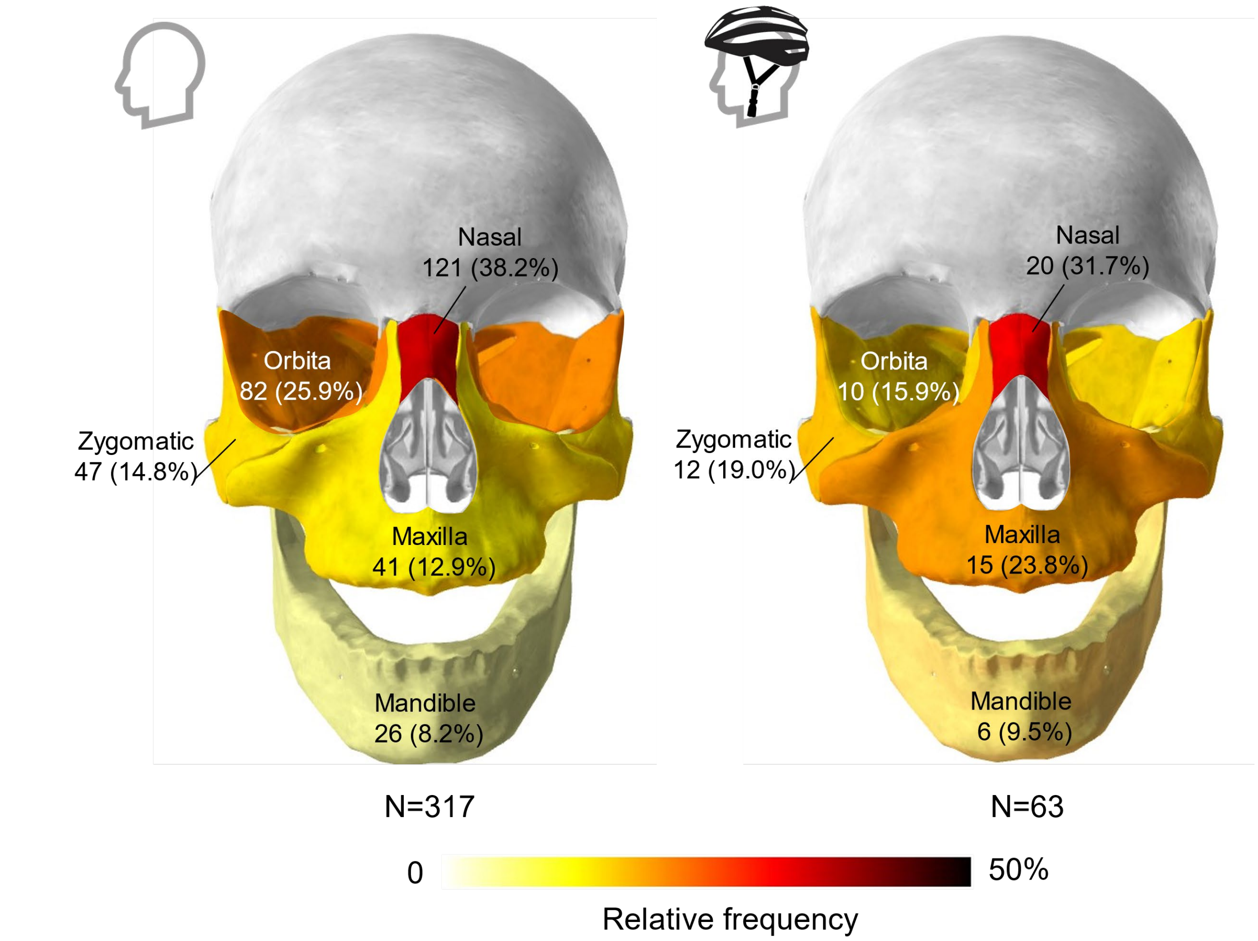

Fig. 3. Frequency distribution of facial fractures for helmeted (right) and unhelmeted (left) bicyclists.

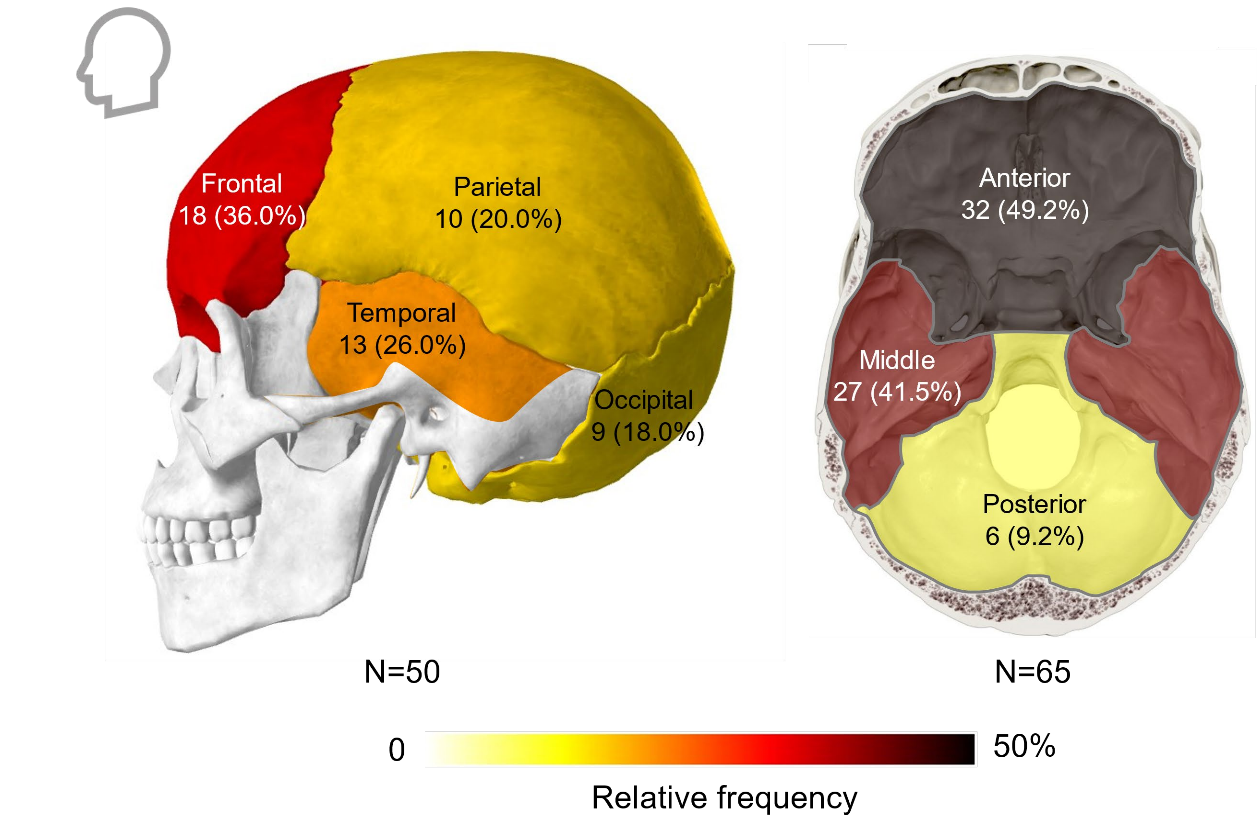

Fig. 4. Frequency distribution of skull vault (left) and skull base (right) fractures for unhelmeted bicyclists.

IV. DISCUSSION

We found different frequency distributions of craniofacial injuries for helmeted and unhelmeted bicyclists using the most recent and detailed injury data from GIDAS (2022 release). In general, facial injuries shifted from the upper face to the mid- and lower face when a helmet was worn. Specifically, for soft tissues, the most frequent facial injuries, shifted from the forehead for unhelmeted bicyclists down to the cheeks, lips and chin for helmeted bicyclists. For skeletal injuries, nasal fractures were most frequent for both unhelmeted and helmeted bicyclists, but the second most frequently fractured site shifted from orbita for unhelmeted bicyclists down to maxilla for helmeted bicyclists. Overall, the mid-face (including nasal, orbita, zygoma, and maxilla) is the most frequently fractured facial region for bicyclists.

A substantial portion of craniofacial injuries, both soft tissue injuries and fractures, were to the face. Approximately two thirds of all injuries were to the face for unhelmeted bicyclists; this proportion is even higher for helmeted bicyclists. The higher proportion of facial injuries for helmeted bicyclists might be explained by the protective effect of helmets reducing skull vault fractures and scalp lacerations, hence reducing the relative proportion of injuries to the head. We can therefore conclude that a protection priority for unhelmeted bicyclists is the forehead (as covered by most helmet standards and helmets), followed by the facial region, which is confirmed when analysing the remaining injuries of helmeted bicyclists. The first priority for head impact protection therefore appears to be for bicyclists to wear a helmet, and the second, for assessment authorities, to efficiently and effectively test facial impact protection, in turn promoting more protective helmet design. In addition to helmet coverage, proper helmet fitting, adjustment, and stability (to avoid the helmet being displaced during normal use or even ejected during a crash) are other key factors for adequate helmet protection [13].

Reference [14] used the same data source as our study (i.e., GIDAS), but a different crash year (i.e., from 1999 to 2011), and presented a similar trend for facial fracture locations of unhelmeted bicyclist (from most common to least common): nasal bone, orbital bone, zygomatic bone, maxilla, and mandible. In contrast, other studies found mandible fractures to outrank other types of facial fractures, with condyle fracture being the most common subtype [11][15-16]. The disparity in injury pattern can be attributed to differences in data collection methodology, scope, and coverage of distinct databases. Reference [15] only included injuries from bicycle falls, and reference [11] also reported the bicycle fall were most common in their database at 62%. A direct (ground) impact to the chin resulting in condyle fractures is a frequent consequence of bicycle falls. In our study, around 31% of bicyclists involved in single bicycle crashes (or falls), while 69% involved in crashes with more than one participant, e.g., a bicyclist collided with a car. A prior study [17] proposed a mechanism of helmet protective effect for the middle face, despite most helmets not providing a protective structure in this region: during a fall, the helmet upper rim and the lower face, together or separately, bear the impact loading from the ground, which avoids direct contact between mid-face region and the ground, Fig. 5 (a). However, we hypothesise that this protective mechanism is insufficient for direct impacts with shaped surfaces, such as impacting a-pillar or roof rail of a car body, or trees in the surrounding environment, Fig. 5 (b). This hypothesis is supported by a comparative study of facial injury pattern between road bicycling (more road surfaces) and mountain biking (more shaped surfaces) finding that mountain bikers sustained higher proportion of severe mid-face fractures such as LeFort I, II and III, but less dental trauma and condylar fractures [18].

Both exposure to impacts and fracture tolerance are factors determining fracture occurrence. The fracture tolerance of facial bones has a large variation regarding both different bones across the face and inter-subject differences. Nasal bones were reported as being the weakest, with the lowest fracture tolerance in the range of 342-450 N [19]. The mandible was found stronger than the maxilla and zygoma but substantially weaker than the frontal bone [20]. The *heatmap* or frequency distribution of facial fractures, Fig. 3, resembles qualitatively these facial fracture tolerances.

Soft tissue injuries (such as skin laceration, avulsion, and contusion) are mostly minor injuries and may therefore not by themselves drive protection priorities, but they provide quantitative real-world data that can be used to estimate the frequency of impact locations. We expanded a previous analysis of soft tissue injuries from unhelmeted bicyclists [8] noting a high relevance of facial impacts also for helmeted bicyclists . An earlier study of soft tissue injury locations and helmet damage supports the conclusion that the face, the frontal and temporal areas on the skull are commonly impacted [21].

The test line prescribed from current bicycle helmet standards is located approximately 10 mm below the hairline, and most commercially available bicycle helmets do not protect the entire facial region (they cover up to the upper third of the facial region). Hence, an extended impact test area covering the mid- and lower face is recommended to be implemented in future standards to assess fracture risks to bones in the mid- and lower face, particularly the maxilla. Furthermore, impacts to the face can not only result in contact forces exceeding the fracture tolerance of facial skeleton, but also generate a moment causing rotation of the head. Rotational motion is the primary injury mechanism for most traumatic brain injuries [22]. We previously showed in experimental tests and a numerical simulation that an impact to the lower face can generate a rapid and large change in head rotation [23]. Reference [3] showed that there is no evidence suggesting facial fracture are protective of traumatic brain injury, instead facial fracture increase the risk of traumatic brain injury among bicyclists. Therefore, facial protection is needed for both reducing facial injuries but also traumatic brain injuries.

For a subset of bicycle helmets, an extended impact test area is already prescribed in standards. ASTM F1952 (Standard Specification for Helmets Used for Downhill Mountain) prescribes a chin bar test where a mass of 5 kg is dropped in a guided fall at 2.8 m/s onto the central portion of the chin guard. The maximum deflection of the chin bar must be less than 60 mm. However, this pass/fail criterion, which is based on a structural requirement rather than human injury tolerance, is not directly related to the assessment of facial fracture or traumatic brain injury risk.

We identified the mid-face as the most prominent region for improving helmet safety. Standards should assess protection; various technical solutions to improve protection appear feasible. A visor (or face shield) in connection with a chin guard likely enhances the safety of current bicycle helmets. However, permanent structure such as chin guards and visors affect field of vision and ventilation during normal use. Airbag-equipped helmets, which deploy an inflatable or expandable structure only when needed, are emerging for head protection [23–25]. They have the potential to offer protection without compromising user comfort when wearing helmets.

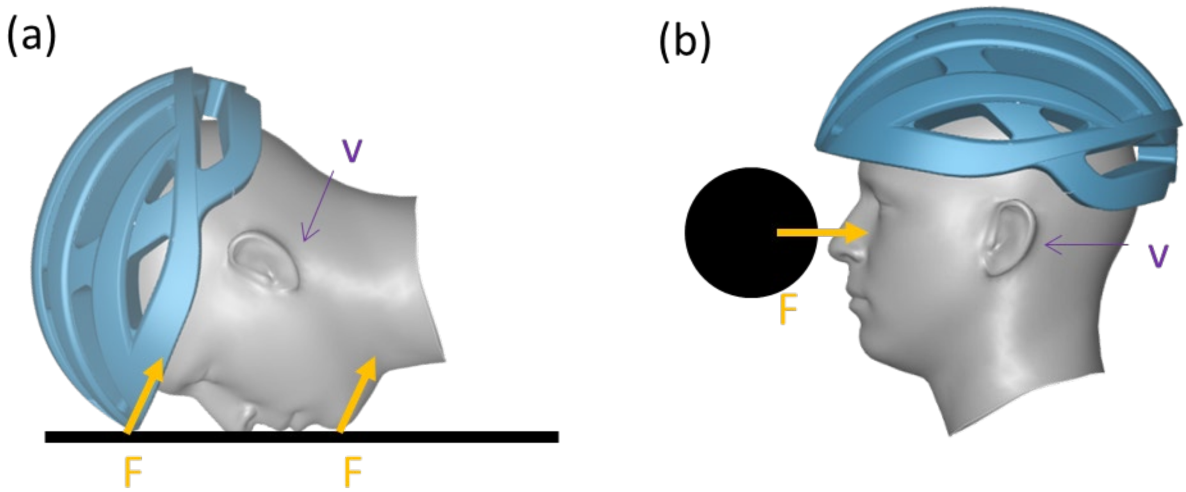

Fig. 5. (a) mechanism of bicycle helmet for protecting mid-face region in a bicycle fall. The helmet rim and the lower-face region together or separately bear the impact loading from the ground, hence avoiding direct contact between the mid-face region and the ground. Adapted from [17]. (b) Insufficient mid-face protection against direct impacts with shaped objects.

V. References

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