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# Quantifying the biotribological properties of forehead skin to enhance head impact simulations

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**Abstract**

Head injury severity is dependent on the loading and accelerations experienced during, and immediately after, impact. In England and Wales alone, for example, 700,000 head injury cases are reported annually within Emergency Departments; however, there remains a lack of data that quantifies the fundamental interaction of the head with an impacting surface. The consequence of impact depends upon a precise understanding of the head–surface interaction; hence, there is a need to appreciate the magnitude of, and variation in, frictional coefficient between the head and a range of possible surfaces. This study develops and validates a novel protocol for quantifying friction between the forehead skin and some potential surfaces. Thirteen participants were recruited and four materials tested, with the lowest (0.11) and highest (1.64) dynamic frictional coefficients measured between skin, and expanded polystyrene and laminate flooring, respectively. Preliminary computational simulation identified that a modest variation in head–surface frictional coefficient (0.6 & 0.7) increases rotational accelerations by 23–33%. Hence, this study highlights the significance of the head–surface interaction, whilst providing some data that will assist investigators evaluating head impacts within both a domestic and sporting environment.


*Keywords:* Forehead; Impact; Injury; Skin; Friction

## 1. Introduction

Head injuries represent a significant national and international health risk. Approximately 700,000 head injury cases are annually reported at Emergency Departments within England and Wales [1]. Injury causation is broad, though common contributors include road traffic collisions, physical assault and sporting accidents [2]. Automotive, forensic and biomechanical engineers are proactively investigating head biomechanics as they seek to simulate the extent of injury severity and efficacy of prevention strategies throughout a wide range of scenarios.

Biomechanical engineers have long been exploring head injury mechanics via both numerical and experimental simulations, generating data that provides insight into the cause and prevention of head/brain trauma. Such simulations have investigated the unprotected head striking, or being struck by, an object (e.g. driver/dashboard interaction in road traffic collisions, civil disputes) [3], whilst other studies have considered similar scenarios with a protected (typically helmeted) head, typically considering motorcyclists and sportspersons respectively [4]. Whilst the complexity of such simulations continues to increase with ever-evolving manufacturing capabilities and computational power, the current literature poorly describes the frictional interaction between the skin and a range of materials. This is particularly true of the forehead, which is of importance, given the propensity for being the primary impact site.

Sivamani et al. [5] describe how skin friction is influenced by a series of inter-linked tribological variables including topology, hydration, underlying material properties, gender and ethnicity, meaning that significant variation exists in data generated from similar studies. Skin water absorption is considered the most influential variable [6,7], with osmosis through to the stratum corneum subsequently influencing the skin topology. This

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principle underpins the functionality of moisturising lotions and cosmetics used to remove age-associated wrinkles. Forehead skin is, though, recognised to be relatively smooth (12–15 μm) [8], whilst comprising a covering of naturally-produced oil-emulsion liquid including water, sweat and sebum. Despite these apparently positive tribological attributes, however, the forehead skin is reported to have a relatively high frictional coefficient [9].

This study aims to quantify the extent and variation of forehead skin friction, during contact with a series of materials that represent some potential impact surfaces. It is hypothesised that the frictional coefficients will vary across the different materials. This result will be highly relevant, both to engineers designing environments that represent a risk of head impact, and to researchers simulating head impact scenarios to deduce, and reduce, injury severity.

## 2. Materials and methods

Thirteen adult participants were recruited to investigate the frictional coefficient between the forehead and a range of materials. All participants provided informed written consent, following approval by the local ethics board.

### 2.1. Skin preparation

Participants were asked to refrain from washing their forehead on the morning of testing, nor to apply any creams or face products during the preceding 24 h. The forehead skin was hydrated before each test by the application of saline-soaked filter paper (Chromatography 17, Whatman plc, England), overlaid with a waterproof Nylon layer, a thin polyester foam and then an elasticated headband. The Nylon prevented the saline from being absorbed by the foam, which in turn, ensured an even application of pressure to the forehead by the headband. A pressure of approximately 2 kPa was applied to the forehead for 20 min, which has previously been deemed appropriate to saturate the skin [10]. Dry filter paper was then applied for 20 s to remove any surface moisture.

### 2.2. Material selection

Each participant was subjected to four materials that individually traversed the forehead, measuring the resisting force to calculate the frictional coefficient of the skin-material interaction. This approach, described schematically in Fig. 1, was determined to best approximate head–surface interaction on impact. Material selection was governed by a desire to investigate a range of characteristics, whilst ensuring that each could be shaped to conform to the forehead curvature. Material selection and preparation is described in Table 1, with each sample flexibly adhered to a 450 × 40 mm inextensible belt. The testing room had an average temperature of 15.6 °C and 43.5% in humidity.

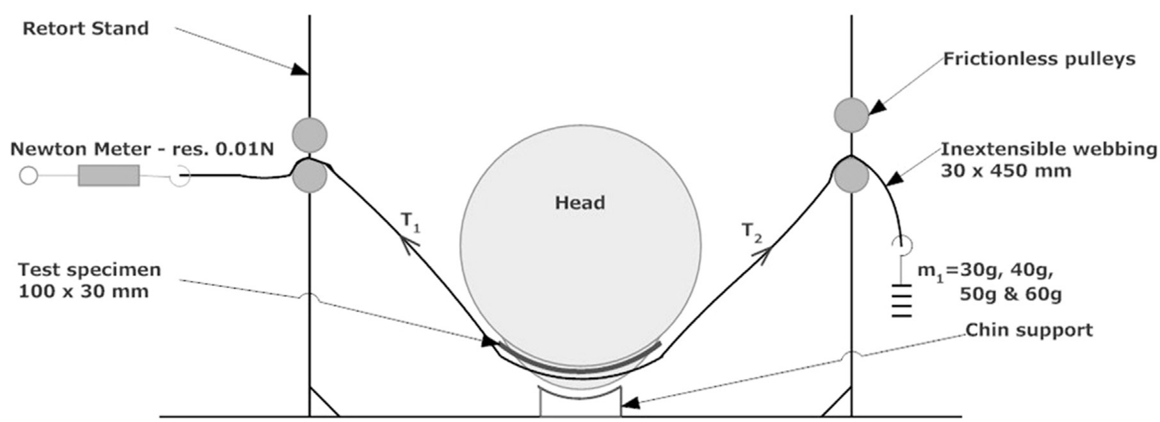


Fig. 1. Schematic summary of novel protocol.

Table 1
The materials selected to investigate a range of forehead–surface frictional coefficients, with each sample measuring 100 × 30 mm (± 1 mm). The stainless steel sample was used only on the forearm, to validate the experimental protocol versus published data.

| Material | Preparation |
|---|---|
| Laminate | The upper layer that had been carefully removed from a laminated flooring surface. The thickness (∼1 mm) ensured that it naturally curved around the forehead. |
| Varnished hardwood ('wood') | Planing a hardwood beam achieved a shaving ∼1 mm thickness. A sample with an appropriate curvature was identified, before this was varnished and adhered to the inextensible band. |
| Carpet | A short-pile nylon carpet was cut to size and adhered to the inelastic band. |
| Expanded polystyrene (EPS) | An appropriately sized section (5 mm thickness) was harvested from the frontal region of an adult cycle helmet. The specimen was already appropriately curved to forehead geometry. |
| Stainless steel | Sheet steel (1 mm thickness) was cut to size and filleted at each corner. The material was then machined to achieve $Ra=0.21$ urn, and curved to the approximate forehead curvature. |

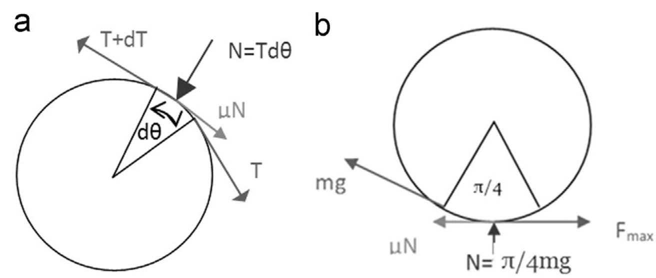


Fig. 2. Schematic representation to describe the derivation of Eq. (7) (a) and 8 (b).

### 2.3. Experimental analysis

Each subject was positioned prone on a bed, with their chin supported on a rest adjusted such that the forehead was approximately horizontal. The surrounding equipment was then adjusted to achieve the setup described in Fig. 1, with an extensometer used to measure the resistance to sliding. The material sample, attached to the belt, was then positioned on the forehead approximately 15 mm below the hairline. The belt was preloaded to achieve static friction (i.e. ‘stiction’) at the forehead–surface interface, with the load increased to ultimately achieve dynamic friction. Both this load and the equivalent extensometer load, was recorded to ultimately calculate the dynamic frictional coefficient.

The dynamic frictional coefficient ($\mu$) can be deduced by applying first principles to Fig. 1, in a manner similar to previous authors [10–12]. Here,$T_1$ is the tension in the taut ($T+dT$) side, $T_2$ is tension in the slack side ($T$), $\mu$ is the coefficient of dynamic friction and $\theta$ is the angle subtended by the belt measured from the horizontal portion of the forehead and testing material:

Resolving the forces in Fig. 2(a) in the $X$-direction:

$$T\cos\partial\theta-(T+\partial T)\cos\partial\theta+\mu\partial N=0 \tag{1}$$

And then in the $Y$-direction:

$$\partial N-T\sin\partial\theta-(T+\partial T)\sin\partial\theta=0 \tag{2}$$

Substituting Eq. (2) into Eq. (1):

$$T\cos\partial\theta-(T+\partial T)\cos\partial\theta=\mu(T\sin\partial\theta+(T+\delta T)\sin\partial\theta=0 \tag{3}$$

Using small angle approximation where $\cos\delta\theta\rightarrow1$, and $\sin\delta\theta\rightarrow\delta\theta$, Eq. (3) becomes:

$$\delta T+(2\mu T+\mu\partial T)\partial\theta=0 \text{ and } \int_{T_1}^{T_2}\frac{1}{T}\partial T=-\int_{\theta}^{0}2\mu\partial\theta \tag{4}$$

Integrating Eq. (4) between the limits:

$$\ln T_2-\ln T_1=2\mu\theta \tag{5}$$

Thus:

$$\frac{T_1}{T_2}=e^{\mu\theta} \tag{6}$$

Or:

$$\mu=\frac{1}{\theta}\ln\frac{T_1}{T_2} \tag{7}$$

Fig. 2(b) denotes $\theta$ is equal to $\pi/4$, $T_1$ is equal to the maximum force to overcome the static friction ($F_{max}$), and $T_2$ is equal to the applied load. Thus, Eq. (7) becomes:

$$\mu=\frac{4}{\pi}\ln\frac{F_{max}}{mg} \tag{8}$$

Data was then statistically assessed using the Students $T$-test (MS Excel) to determine whether the frictional coefficient varied across the different skin-material interactions.

### 2.4. Experimental validation

Eleven participants were subjected to a further test, using identical principles to quantify the frictional coefficient of forearm skin versus a stainless steel surface. This protocol was similar to Veijgen [13], allowing assessment of data comparability and thus experimental validity.

### 2.5. Numerical analysis

A preliminary numerical analysis was performed to investigate the potential consequence of any frictional coefficient variation on head injury severity. A ‘headform’ (i.e. a geometric, mass appropriate representation of the human head) was developed (circumference=531 mm; mass=3.66 kg) in the ADAMS multi-body simulation software. The impact characteristics were parametrically iterated until the simulation produced valid headform acceleration data versus Mertz et al. [14]. An exemplar impact scenario was then devised with an impact velocity of 8.2 m/s on to a steel surface, angled 15° to the vertical plane, to induce head rotation. Impacts were then performed in configurations of: (i) ‘nose down’, with initial contact on the vertex; (ii) ‘nose down’, with initial contact on the temporal bone; (iii) ‘ear down’ with initial contact on the vertex. These scenarios produced rotational accelerations about the sagittal, coronal and frontal planes, respectively. Each

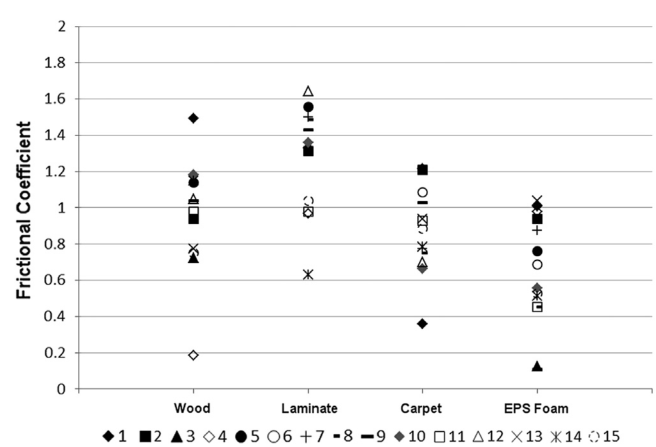


Fig. 3. The static frictional coefficient describing the forehead–surface contact, across 13 participants.

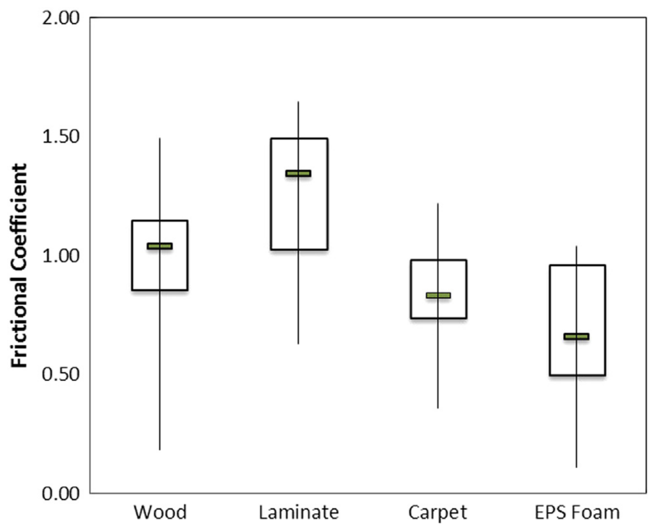


Fig. 4. Box and whisker plots describing the median, first and third quartile of each dataset.

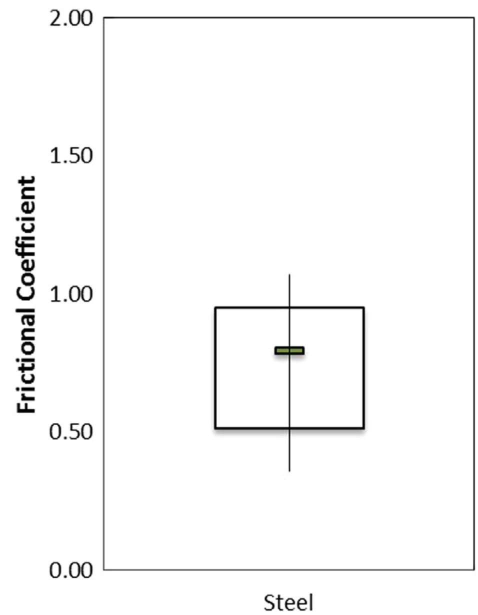


Fig. 5. Data describing the static frictional coefficient between the forearm and a steel surface.

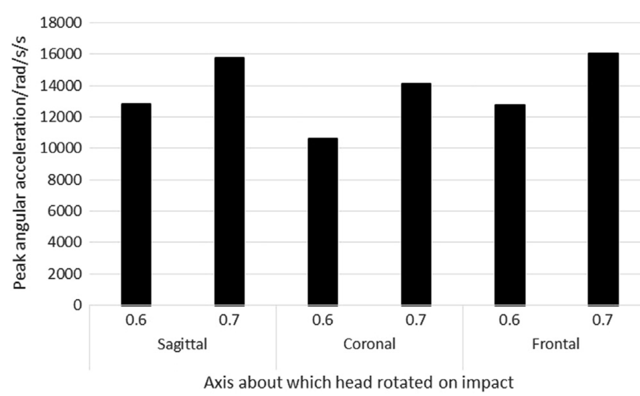


Fig. 6. Rotational head acceleration data when considering impact with an inclined steel plane, with two frictional coefficients.

scenario was then investigated considering a modest difference in head–surface frictional coefficients (0.6 and 0.7).

## 3. Results

### 3.1. Experimental analysis

Experimental data was collected from all participants ($n=13$) for the carpet and EPS foam materials, though for only 12 participants when testing the wood and laminate materials. The frictional coefficient of forehead skin ranged from 0.11–1.64 across all tests, with little consistency evident in frictional coefficient across the population. Participant 1, for example, exhibited the highest coefficient when exposed to wood, though the lowest for carpet (Fig. 3).

The frictional coefficients differed statistically when considering each material (i.e. $p<0.05$), with the polymer veneer representing the greatest resistance when being slid across the forehead (mean $\mu=1.27$), being approximately 2-fold greater than the EPS foam (mean $\mu=0.68$). Mean frictional coefficients of 0.97 and 0.85 were recorded for wood and carpet surfaces, respectively. The extent of variation evident in the data presented in Fig. 4 provides an indication of the multi-factorial contribution to measuring the skin frictional coefficient, with the skin–wood coefficients ranging from the lowest (0.18) to the near-highest (1.49) of all recorded data. The experiments relying upon the synthetic materials produced less varied data, with the carpet ranging from 0.36 to 1.22.

### 3.2. Experimental validation

The mean, dynamic frictional coefficient for the forearm–steel interaction (0.71) was measured to assist in determining the validity of this experimental technique versus previous studies. The interquartile range equalled 0.45, whilst Fig. 5 provides further data that describes the median and data distribution across the 11 participants. The surface roughness of the stainless steel was measured using a Talysurf profilometry machine (average $Ra=0.21$ μm).

### 3.3. Numerical analysis

Acceleration data was generated for each head impact onto a steel plane, inclined 15° to the vertical (Fig. 6). The 'nose down, vertex' impact produced 12,790 rad s$^{-2}$ about the *sagittal* plane when investigating with the lower frictional coefficient. The rotational acceleration increased by 23% when the dynamic friction was defined at 0.7. During the 'nose down, temporal' impact, a reduced rotational acceleration was measured (10,583 rad s$^{-2}$) in the *coronal* plane, when applying the conservative frictional conditions. Rotational acceleration increased by 33% at the higher frictional coefficient. The 'ear down, vertex' impact generated 12,774 rad s$^{-2}$ about the *frontal* plane, with a 25% increase with a frictional coefficient equal to 0.7. All data was collected during simulation runs for 0.9 s, over 1000 calculation steps.

## 4. Discussion

This study developed a novel technique that allowed measurement of the frictional coefficient at the interface of the forehead and an opposing surface. The data presented here not only highlights the variation that exists when considering such interactions, but also demonstrates the importance of precisely modelling this interaction given the consequent effect on post-impact head dynamics. Hence, such data is valuable to researchers investigating the cause of, and strategies mitigating against, head injury through impact.

The validity of this new technique was evaluated by performing a series of investigations quantifying the frictional coefficient between the forearm and a stainless steel surface. The mean frictional coefficient described in Fig. 5 (0.71), compared favourably to comparable data reported by Veijgen (0.62) [13]. Further validation is provided by the similar interquartile ranges reported in this study (0.45), versus Veijgen (0.62) [13].

The frictional coefficient of forehead skin ranged from 0.18 to 1.64 across all tests, with little consistency evident in frictional coefficient across the population. Participant 1, for example, exhibited the highest coefficient when exposed to wood, though the lowest for carpet (Fig. 3). The importance of considering the impacting surface is highlighted when noting the statistical significant evident between each material. The laminate surface presented the greatest resistance for the majority of participants (Figs. 3 and 4); however, it also demonstrated how the precise behaviour is participant–dependant, given the approximately 3-fold difference between the minimum ($\mu=0.63$; Participant 12) and maximum values ($\mu=1.64$; Participant 10). The laminate mean frictional coefficient ($\mu=1.27$) was approximately 2-fold greater than the lowest mean value (EPS foam; mean $\mu=0.68$). Indeed, a 2-fold difference is noted throughout the majority of this data, assuming that Participant 7 ($\mu=0.11$) represents anomalous data. The EPS foam data is significant given that this material serves as the primary load-bearing structure in protective cycling and motorcycling helmets. This low frictional coefficient would indicate that there is a propensity for slippage between this surface and the skin on impact, potentially preventing transfer of some impact energy to the head and potentially reducing injury severity.

Mean frictional coefficients of 0.97 and 0.85 were recorded for wood and carpet surfaces, respectively. The extent of variation evident in the presented data provides further evidence of the multi-factorial influences when measuring skin friction, with the skin–wood coefficients ranging from the lowest (0.18) to the near-highest (1.49) of all recorded data. The experiments relying upon the synthetic materials typically produced less variation, with the carpet data ranging from 0.36 to 1.22.

Fig. 6 describes the importance of assigning accurate contact parameters to the skin-impact material interaction. A modest increase in frictional coefficient (from 0.6 to 0.7) produced a 23% increase in rotational acceleration of the head when considering an impact in the sagittal plane. Greater differences were noted when examining an impact from the frontal plane (25% increase) and coronal plane (33%). This preliminary analysis highlights the risk associated with using inaccurate frictional data, as engineers may reach inaccurate conclusions when evaluating the effectiveness of head protection system, the outcome of crash scenarios, or the cause of sports injuries.

## 5. Conclusions

This investigation has evaluated some forehead–surface interactions, quantifying the frictional coefficient variation. Additionally, the intra-population variability has been highlighted. A preliminary study has also demonstrated how the frictional coefficient can influence head dynamics post-impact, which is likely to directly influence injury severity. It is anticipated that this data will be of interest to researchers exploring head injury biomechanics across a range of sectors.

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