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The Influence of Friction Between Football Helmet and Jersey Materials on Force: A Consideration for Sport Safety

Anthony M. Rossi, MSc; Tina L. Claiborne, PhD; Gregory B. Thompson, PhD; Stacey Todaro, PhD

Athletic Training, Adrian College, MI

Context: The pocketing effect of helmet padding helps to dissipate forces experienced by the head, but if the player's helmet remains stationary in an opponent's shoulder pads, the compressive force on the cervical spine may increase.

Objective: To (1) measure the coefficient of static friction between different football helmet finishes and football jersey fabrics and (2) calculate the potential amount of force on a player's helmet due to the amount of friction present.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Helmets with different finishes and different football jersey fabrics.

Main Outcome Measure(s): The coefficient of friction was determined for 2 helmet samples (glossy and matte), 3 football jerseys (collegiate, high school, and youth), and 3 types of jersey numbers (silkscreened, sublimated, and stitched on) using the TAPPI T 815 standard method. These measurements determined which helmet-to-helmet, helmet-to-jersey number, and helmet-to-jersey material combination resulted in the least amount of static friction.

Results: The glossy helmet versus glossy helmet combination produced a greater amount of static friction than the other 2 helmet combinations ($P = .013$). The glossy helmet versus collegiate jersey combination produced a greater amount of static friction than the other helmet-to-jersey material combinations ($P < .01$). The glossy helmet versus silkscreened numbers combination produced a greater amount of static friction than the other helmet-to-jersey number combinations ($P < .01$).

Conclusions: The force of static friction experienced during collisions can be clinically relevant. Conditions with higher coefficients of static friction result in greater forces. In this study, the highest coefficient of friction (glossy helmet versus silkscreened number) could increase the forces on the player's helmet by 3553.88 N when compared with other helmet-to-jersey combinations. Our results indicate that the makeup of helmet and uniform materials may affect sport safety.

Key Words: static friction, pocketing effect, axial compression, cervical spine, football uniforms, epidemiology

Key Points

- The force of a collision in football ranges from 3922 to 7845 N, with neck failure occurring at forces as low as 3340 to 4450 N. When a football player initiates contact via spearing, his head can compress the shoulder pads and other soft tissues of an opponent and essentially create a pocket that holds the head in place.
- A padded surface with low friction may be ideal not only to allow for absorption of impact forces but also to permit the head to slide out of the pocket and avoid compressive forces from the oncoming player's torso.

The 1960s were a time of growing popularity for organized athletics. This increased attention to and involvement in sport resulted in an increase in serious athletic injuries. In response, the National Operating Committee on Standards for Athletic Equipment (NOCSAE) was developed in 1969 to accredit research directed toward injury reduction in athletes. The NOCSAE is now the leading organization developing standards for protective equipment in a variety of sports. In American football, 1 purpose of the NOCSAE standards was to establish guidelines that maximized the protective capabilities of football helmets. In the 1970s, the implementation of the NOCSAE helmet safety standards resulted in a significant decrease in traumatic brain injuries and deaths in American football players.[1] However, an unforeseen side effect of these new safety standards was an increase in catastrophic cervical spine injuries as a result of spearing.[2,3]

According to Banerjee et al,[2] when axial loading occurs as a result of spearing, 2 patterns of spinal column damage are common: flexion-teardrop and burst fractures.[2] The 3 factors that can lead to flexion-teardrop or burst fractures are the location of impact, neck buckling, and the *pocketing effect*. The pocketing effect is a contributor to injury that is not frequently discussed in the literature. When a player spears an opponent, the former's head can compress the protective padding or the soft tissue of the latter and essentially create a pocket that holds the head in place.[4–6] A pocketing effect that occurs in the padding of a helmet is desirable because it helps to dissipate the forces exerted on the head. Yet if an athlete's helmet remains stationary, or sticks in the pocket of an opponent's shoulder pads, the

Table 1. Jersey Descriptions

Jersey Type	Material[a]	Numbers	Manufacturer
Collegiate	Body: 86% nylon, 14% spandex Mesh: 88% nylon, 12% spandex	Stitched on twill	Nike, Inc (Beaverton, OR)
High school	Colored sections: 100% nylon White sections: 100% polyester	Silkscreened	Russell Athletic (Bowling Green, KY)
Youth	Body: 100% polyester	Sublimated	Alleson Athletic (Rochester, NY)

[a] Indicates section of material that was tested.

compressive force experienced by the cervical spine may be exacerbated. The head may not be able to effectively flex and move out of the path of the oncoming torso, resulting in a longer time during which the cervical spine is exposed to compressive forces.[4–6] Because padding is necessary to protect athletes from catastrophic injuries (eg, skull fractures), athletic trainers and other health professionals should be aware of the pocketing effect.[4–6]

In the pocketing effect, friction between colliding surfaces affects the magnitude of force that may ultimately be transferred to the body. A *force* is any agent that causes a change in motion, and *friction* is a force that opposes motion or potential motion. Specifically, *static friction force* (f_s) can be defined as the force that must be overcome to initiate sliding between 2 materials.[7] Intuitively, we expect an increase in f_s between the helmet and jersey surfaces to decrease the ability of the head to move out of the pocket or glance off an opposing surface. If more force is necessary to overcome static friction, the head may remain stuck in position, thereby increasing the duration of excessive loads on the body.

Nightingale et al[6] demonstrated the influence of static friction on cervical spine injuries in cadavers. They performed drop testing on cadaveric neck models to simulate axial compression injuries. Seven of their specimens were impacted with a steel plate that was covered with a sheet of lubricated Teflon (low-friction, rigid surface; The Chemours Company, Wilmington, DE). Four specimens were impacted with a surface covered by 5 cm of open-cell polyurethane foam (high-friction, padded surface). The foam created a pocket around the head that prevented it from sliding along the impact surface, and the high-friction, padded surface resulted in more neck injuries due to buckling.[6] It is also interesting to note that the injuries from the low-friction, rigid surface occurred in a span of 2.2 to 8.3 milliseconds, whereas the injuries from the high-friction, padded surface occurred in 14.8 to 18.8 milliseconds.[6] These findings demonstrate how the pocket created by the padded surface increases the amount of time that the cervical spine is exposed to compressive forces. These results may indicate that a low-friction padded surface would be ideal to allow impact forces to be absorbed but also allow the head to slide out of the pocket to avoid compressive forces from the oncoming player's torso. Given the work of Nightingale et al,[6] it may be important to consider ways to diminish the pocketing effect. For example, decreasing the static friction between the helmet and jersey may encourage the helmet to slide out of the pocket, thereby decreasing the potential for axial compression of the cervical spine. The research of Nightingale et al[6] is similar to that of Camacho et al[8] regarding the influence of padding properties on the risk of head and neck injury. Choosing a pad that allows for maximal deformation as well as minimal surface friction could decrease injury risk.[8] Therefore, our goal was to demonstrate the influence of static friction between helmet material and jersey material on the overall force of a collision. These findings could permit us to identify which materials best reduce the risk of head and neck injury based on their coefficient of static friction (μ_s). Future studies will be necessary to identify which padding materials could be used with these low-friction materials to dissipate maximal energy.

Some may argue that athletic trainers do not influence the uniform materials used by manufacturers and that research in this area is fruitless. However, recent scientific inquiry has resulted in modifications to modern protective equipment, including helmet and facemask design. Therefore, advancing knowledge in this area may drive equipment managers, purchasers, or manufacturers to consider other options when determining the safest choices for their athletes. Thus, the purposes of our study were to (1) measure μ_s between different football helmet finishes and football jersey fabrics and (2) calculate the potential amount of force that the cervical spine could experience due to friction.

METHODS

Materials

Three samples each of glossy and matte helmet finishes were used for data collection. A glossy helmet begins as an unpainted shell, and then color is injected into the plastic or polycarbonate material at the time of molding, leaving a slight sheen. A matte helmet color is created by paint with a dulling agent added to reduce shine and luster. Three jerseys that represent common styles for youth, high school, and collegiate football teams were used for data collection, and their descriptions are found in Table 1. Both the body fabric of each jersey and the numbers were tested against both helmet finishes. The apparatus used for testing consisted of an inclined plane, a 49.6-oz (1.4-kg) aluminum block, a means to increase the angle of inclination at a rate of 1.5°/s ± 0.5°/s from the horizontal plane through an arc of 60°, and a means to indicate the angle of inclination within 1.0°.

The testing apparatus was used to determine μ_s between 2 surfaces using the Technical Association of the Pulp and Paper Industry (TAPPI) T 815 standard method.[9] This procedure was originally developed to test μ_s between packing materials. This is the first study, to our knowledge, to use this method in an application for sports safety. The repeatability and reproducibility of this testing procedure on untreated, uncoated packing papers were 6% and 15%, respectively.

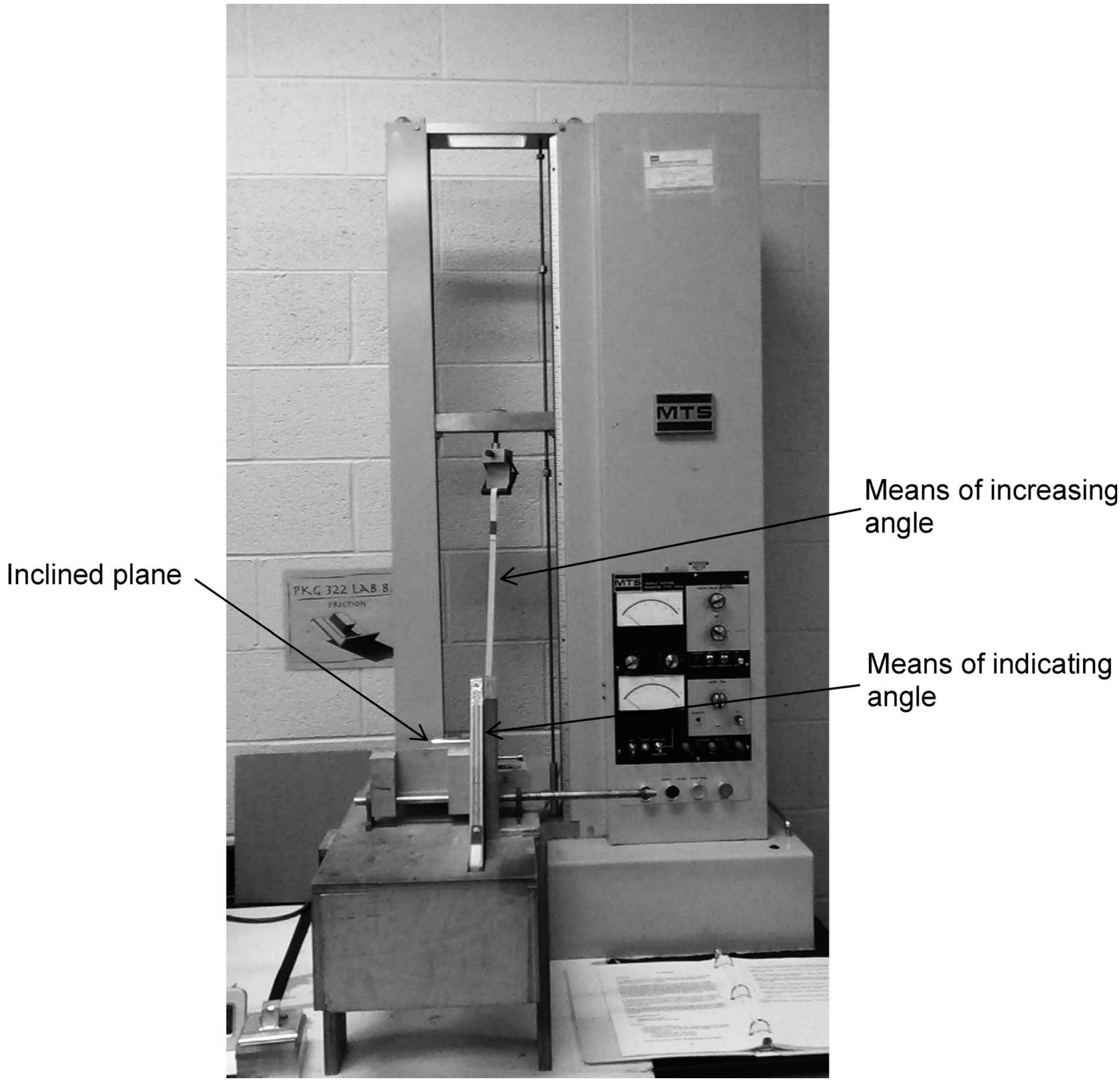

Figure 1. Overview of testing machine.

Procedure

All testing preparations, procedures, and calculations were adapted from the TAPPI T 815 standard method. Because this protocol addresses the use of untreated, uncoated packing papers, we made slight variations to accommodate the materials used in this study. The TAPPI standard calls for new samples of testing material for every set of 3 trials; however, due to the limited supplies available for this study, the 3 samples of both the glossy and matte helmet finishes were rotated for every set of trials. The TAPPI standard also calls for recording the angle of inclination to the nearest 0.5°, but the machine we used had markings to record the angle only to the nearest 1.0°. Helmet samples rather than actual helmets were used for testing due to the machine for measuring μ_s: as seen in Figure 1, the testing surface is too small for an entire helmet. On the macroscopic level, the coefficient of friction is independent of surface area. Therefore, the use of a flat helmet sample, as opposed to a rounded helmet, will not affect the measurements.[10]

Preparation of Testing Materials. To assess all test combinations, a total of 10 samples for each jersey material (5 samples from the body of the jersey) and number (5 samples of the number associated with each jersey) were required. Three samples of each helmet finish (2-in [5.08-cm] wide, 3-in [7.62-cm] long, and 0.25-in [0.64 cm] thick) were used. The jersey material and number samples were cut slightly larger than the size of the helmet-finish samples to permit sliding of the aluminum block.

Testing. The room's temperature, humidity, and pressure were recorded before and after data collection. The inclined plane was placed in the horizontal position, at 0°. One helmet-finish sample was mounted on the aluminum block using double-sided tape, with the surface to be tested facing downward. The other specimen (helmet finish, jersey material, or jersey number) was mounted on the inclined plane using a metal clip with the surface to be tested facing upward. The aluminum block was placed on top of the specimen on the inclined plane away from the hinge and stop. An overview of the testing machine is shown in Figure 1.

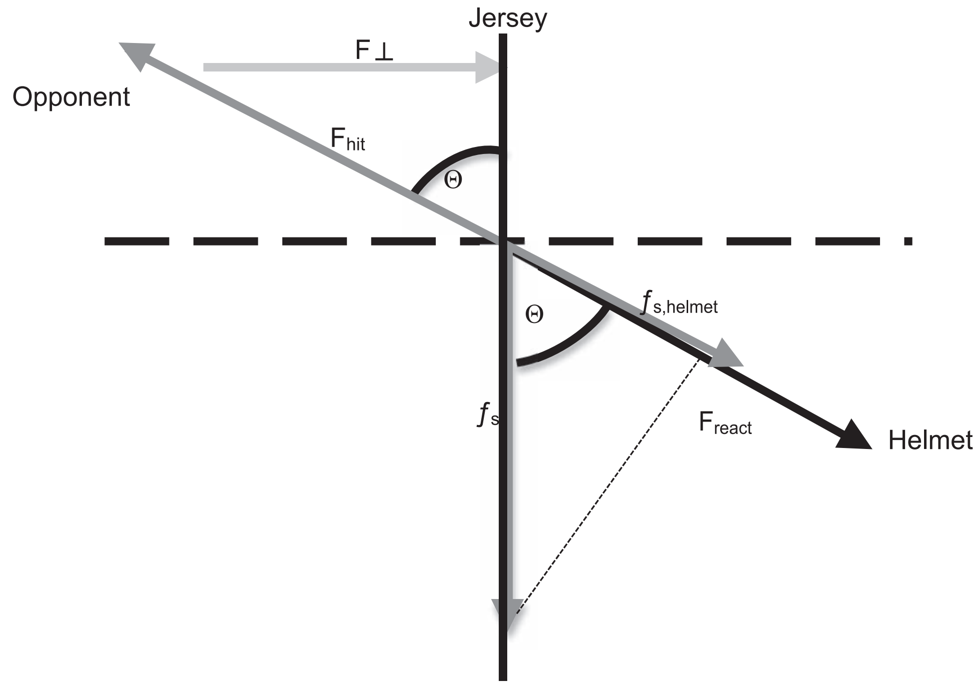

Figure 2. Force experienced during a collision. Abbreviations: Θ, angle of collision (°); $F_\perp$, perpendicular force (N); F_{react}, force experienced by the tackler in the opposite direction; f_s, total static friction force (N); $f_{s,helmet}$, portion of f_s experienced by the helmet (N).

The tensile testing machine was turned on, and the crosshead switch was turned to the up and tension position. The crosshead speed indicator was set to 500 mm/min, and the crosshead speed knob was set to 300 mm/min. A dwell time of 10 seconds was allowed before beginning all trials, and then the angle of inclination was increased at a rate of 1.5°/s ± 0.5°/s by pressing the green start button. The fine crosshead control knob was used to maintain a speed of 30 mm/min. Pressing the red stop button when the aluminum block began to move stopped the incliner. The block was allowed to slide to the hinge and stop. The inclined plane was then returned to the horizontal position by turning the crosshead switch to down and depressing the start button. To begin the next trial, the aluminum block was returned to the starting position. This procedure was repeated for 3 trials for each testing combination. Only the angle at which sliding occurred during the third trial was used for calculations to the nearest 1.0°. Per the TAPPI T 815 standard method,[9] the first 2 angles were not recorded in order to account for any dust or particles that may have accumulated on the test specimens before testing. New pieces of the same 2 test specimens were mounted on the aluminum block and inclined plane for each set of 3 trials. A total of 15 trials were performed with each combination of testing materials in order to provide 5 angles of inclination. This study had a counterbalanced design, so the entire procedure was repeated for each helmet-to-helmet, helmet-to-jersey number, and helmet-to-jersey material combination. After testing, the room's temperature was 22.3°C, humidity was 54.3%, and pressure was 968 mb (96800 Pa).

Calculations. We calculated μ_s for each set of 3 trials by finding the tangent of the angle of inclination that was recorded. The average μ_s was determined from the 5 sets of trials for each testing combination.

Data Analysis

Calculations to determine μ_s from each angle of inclination were performed using Excel (Microsoft Corp, Redmond, WA). The SPSS software (version 22; IBM Corp, Armonk, NY) was used to compare the average μ_s from each testing combination. Once the lowest and highest combinations of helmet-to-helmet, helmet-to-jersey number, and helmet-to-jersey material were determined by comparing the μ_s, the total f_s for those combinations were calculated. Finally, the portion of the f_s that could potentially be exerted on a player's helmet ($f_{s,helmet}$) was calculated and used to estimate the total amount of force that could be transmitted to the body during a collision ($F_{Total} = F_{react} + f_{s,helmet}$), based on the different μ_s and collision angles.

After using the μ_s to determine the lowest and highest combinations of the helmet-to-helmet, helmet-to-jersey number, and helmet-to-jersey material combinations, the total amount of f_s present during a collision was calculated in newtons. The f_s was generated from the equation $f_s = \mu_s F_\perp$, where μ_s was from the particular combination and $F_\perp$ was the normal force that was experienced during a collision and measured in newtons. Here, $F_\perp$ is the component of a collision that was perpendicular to the jersey. The $F_\perp$ was obtained from the equation $F_\perp = F_{hit} \sin\Theta$, where F_{hit} was the estimated force of a collision, and Θ was the angle at which a collision may occur, measured counterclockwise from or relative to the plane of the jersey.

A previous researcher[4] determined that the greatest amount of force experienced during direct collisions ranged from 3922 to 7845 N, so we used these minimum and maximum forces for the F_{hit}. The Θ represented every 10° angle from 0° to 90°. However, the 0° angle was replaced with a 5° angle because there would be no normal force in that case. Also, a direct collision at a 90° angle would result in all of the impact force being perpendicular to the

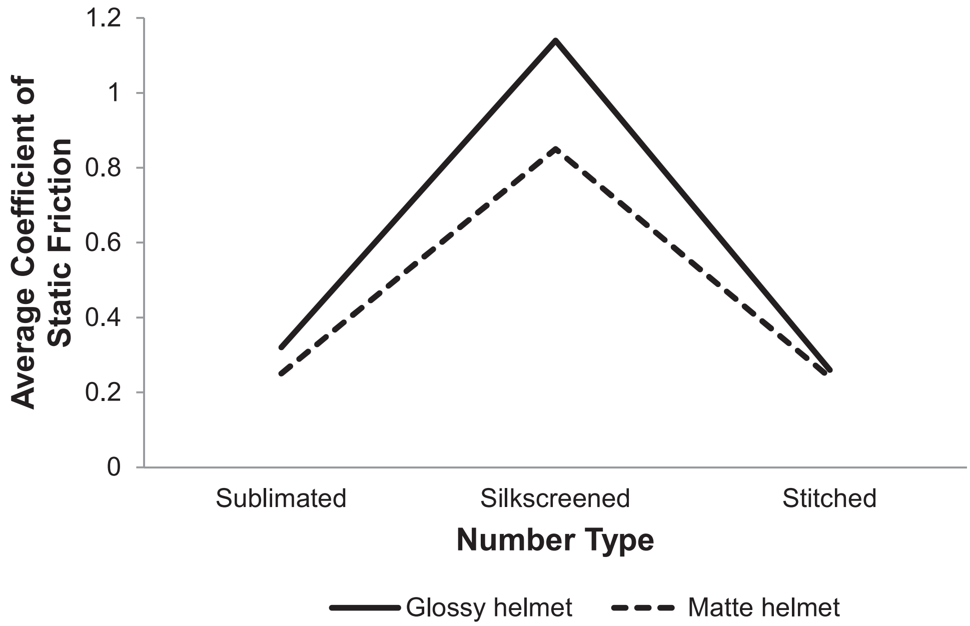

Figure 3. Interactions between helmet type and jersey number type.

opponent and no parallel component trying to initiate sliding; therefore, it was replaced by an 85° angle. This calculation was performed to obtain an $F_{\perp}$ for a collision occurring at every Θ using both 3922 and 7845 N as the F_{hit}. Once the $F_{\perp}$ of a particular collision was calculated, it was used to determine the total amount of f_s present during the lowest and highest helmet-to-helmet, helmet-to-jersey number, and helmet-to-jersey material collisions at various angles.

The Newton third law of motion states that, for every force, there is a reaction force that is equal in size but opposite in direction. Therefore, the force that is experienced by a player who is being tackled (F_{hit}) is the same as that experienced by the tackler in the opposite direction (F_{react}). For these purposes, $F_{hit} = F_{react}$. If we assume that, during a spearing tackle, the F_{react} is to the crown of a player's helmet, then the component of f_s that is at the crown of the helmet is $f_{s,helmet} = f_s \cos\Theta$, where Θ is the angle at which the collision occurred. A portion of the f_s is dissipated along the contact surface, so the tackler experiences only a portion of f_s, which is defined as $f_{s,helmet}$ (Figure 2). Thus, the total amount of force experienced by a player's head during a collision was determined by the equation $F_{Total} = F_{react} + f_{s,helmet}$.

The values of F_{Total} between the lowest and highest combination of the helmet-to-helmet, helmet-to-jersey number, and helmet-to-jersey material combinations were compared to demonstrate how much the estimated collision force could be influenced by the μ_s between the surfaces.

RESULTS

Testing Environment

We performed this study in a climate-controlled facility that does not simulate an outdoor sports environment. Because the environment may affect the surface of the materials, we thought it was important to note the temperature, humidity, and barometric pressure. Before testing, the room temperature was 22.1°C, humidity was 51.8%, and pressure was 975 mb (97500 Pa). After testing, the room temperature was 22.3°C, humidity was 54.3%, and pressure was 968 mb (96800 Pa).

Coefficient of Static Friction Between Surfaces

A series of analyses of variance were conducted to determine if mean differences existed in μ_s between surfaces. For each analysis, the independent variable was the surface type (eg, glossy helmet, stitched jersey), and the dependent variable was the average μ_s across 5 trials. Post hoc analyses were conducted using the Bonferroni correction. The rejection level for all analyses was set at the .05 level.

Table 2. Total Force Experienced During Glossy Helmet Versus Glossy Helmet and Matte Helmet Versus Matte Helmet Collisions at a 60° Angle

Combination	Collision Force, N	μ_s	$F_{\perp}$	f_s	$f_{s,helmet}$	F_{Total}
Glossy helmet versus glossy helmet	3922	0.44	3396.55	1494.48	747.24	4669.24
Matte helmet versus matte helmet	3922	0.26	3396.55	883.10	441.55	4363.55
Glossy helmet versus glossy helmet (N)	7845	0.44	6793.97	2989.35	1494.67	9339.67
Matte helmet versus matte helmet	7845	0.26	6793.97	1766.43	883.22	8728.22

Abbreviations: μ_s, coefficient of static friction; $F_{\perp}$, perpendicular force (N); f_s, total static friction force (N); $f_{s,helmet}$, portion of f_s experienced by the helmet (N); F_{Total}, total force experienced during the collision.

Table 3. Total Force Experienced During Glossy Helmet Versus Silkscreened Numbers and Matte Helmet Versus Sublimated Numbers Collisions at a 60° Angle

Combination	Collision Force, N	μ_s	$F_\perp$	f_s	$f_{s,helmet}$	F_{Total}
Glossy helmet versus silkscreened numbers	3922	1.14	3396.55	3872.07	1936.03	5858.03
Matte helmet versus sublimated numbers	3922	0.22	3396.55	747.24	373.62	4295.62
Glossy helmet versus silkscreened numbers (N)	7845	1.14	6793.97	7745.12	3872.56	11717.56
Matte helmet versus sublimated numbers	7845	0.22	6793.97	1494.67	747.34	8592.34

Abbreviations: μ_s, coefficient of static friction; $F_\perp$, perpendicular force (N); f_s, total static friction force (N); $f_{s,helmet}$, portion of f_s experienced by the helmet (N); F_{Total}, total force experienced during the collision.

Helmet to Helmet. Helmet combinations demonstrated a main effect ($F_{2,8} = 7.85$, $P = .01$, $\eta_p^2 = 0.66$). The glossy versus glossy helmet combination produced a greater amount of static friction (mean ± SD = 0.44 ± 0.10) than both the matte versus matte (0.27 ± 0.04) and the glossy versus matte helmet (0.37 ± 0.04) combinations. The matte versus matte helmet combination and the glossy versus matte helmet combinations did not differ.

Helmet to Jersey Number. Post hoc analysis revealed a significant interaction between helmet type and jersey number type ($F_{2,24} = 37.88$, $P < .01$, $\eta_p^2 = 0.93$). As seen in Figure 3, the glossy helmet versus silkscreened number combination produced a greater amount of static friction than the other helmet-to-jersey number combinations. No other mean differences were significant.

A 2 (helmet: glossy versus matte) × 3 (jersey number: stitched, silkscreened, sublimated) factorial analysis of variance revealed a main effect of helmet ($F_{1,24} = 100.41$, $P < .01$, $\eta_p^2 = 0.97$). The glossy helmet produced a greater amount of static friction (0.57 ± 0.03) than the matte helmet (0.45 ± 0.01). Jersey type also demonstrated a main effect ($F_{2,24} = 1400.61$, $P < .01$, $\eta_p^2 = 1.00$). Silkscreened numbers produced more static friction (1.00 ± 0.04) than the sublimated (0.29 ± 0.01) and stitched (0.25 ± 0.01) numbers. There was no difference between the sublimated and stitched numbers.

Helmet to Jersey Material. A 2 (helmet: glossy versus matte) × 3 (jersey type: collegiate, high school, and youth) factorial analysis of variance revealed a main effect of helmet ($F_{1,12} = 232.07$, $P < .01$, $\eta_p^2 = 0.98$). The glossy helmet generated more static friction (0.32 ± 0.01) than the matte helmet (0.25 ± 0.02). Jersey type also revealed a main effect ($F_{2,12} = 93.27$, $P < .01$, $\eta_p^2 = 0.94$). The collegiate jersey produced more static friction (0.32 ± 0.04) than the high school jersey (0.29 ± 0.03) and youth jersey (0.25 ± 0.04). The interaction between helmet type and jersey type was not significant ($F_{2,12} = 0.87$, $P > .01$, $\eta_p^2 = 0.34$).

Force Calculations. The lowest μ_s was with the matte helmet versus matte helmet combination, and the highest μ_s was with the glossy helmet versus glossy helmet combination. To demonstrate the significance of the difference between these μ_s values, the total f_s, $f_{s,helmet}$, and F_{Total} $f_{s,helmet}$, and F_{Total} resulting from glossy helmet versus glossy helmet and matte versus matte helmet collisions of 3922 and 7845N at 60° are shown in Table 2.

The helmet-to-jersey number combination with the lowest μ_s was the matte helmet versus sublimated numbers and with the highest μ_s was the glossy helmet versus silkscreened numbers. The f_s, $f_{s,helmet}$, and F_{Total} resulting from glossy helmet versus silkscreened numbers and matte helmet versus sublimated numbers collisions of 3922 and 7845 N at 60° are available in Table 3.

The helmet-to-jersey material combination with the lowest μ_s was the matte helmet versus youth jersey and with the highest μ_s was the glossy helmet versus collegiate jersey. The f_s, $f_{s,helmet}$, and F_{Total} resulting from glossy helmet versus collegiate jersey and matte helmet versus youth jersey collisions of 3922 and 7845 N at 60° are provided in Table 4.

DISCUSSION

Football collisions range from 3922 to 7845 N, with neck failure occurring at forces as low as 3340 to 4450 N. When a football player initiates contact via spearing, his head can compress the shoulder pads and other soft tissues of an opponent and essentially create a pocket that holds the head in place[4–6]: the pocketing effect. An increase in friction between surfaces will likely cause the head to remain in the pocket longer, thereby increasing the time the head and neck are exposed to collision forces. Consequently, it is beneficial to understand the potential effect of increased friction between helmet and jersey surfaces on the typical collision forces exhibited in football.

Because the coefficient of friction is not fundamentally a force, it is important to comprehend the relationship between μ_s and the force of friction. The coefficient of friction is the ratio of friction forces between surfaces and the force necessary to commence sliding of 1 surface over another. When the coefficient of friction is used to calculate the force (N), the meaning becomes more clinically relevant. A condition with a higher μ_s results in higher forces. The purpose of our study was to determine the μ_s

Table 4. Total Force Experienced During Glossy Helmet Versus Collegiate Jersey and Matte Helmet Versus Youth Jersey Collisions at a 60° Angle

Combination	Collision Force, N	μ_s	$F_\perp$	f_s	$f_{s,helmet}$	F_{Total}
Glossy helmet versus college jersey	3922	0.36	3396.55	1222.76	611.38	4533.38
Matte helmet versus youth jersey	3922	0.22	3396.55	747.24	373.62	4295.62
Glossy helmet versus college jersey	7845	0.36	6793.97	2445.83	1222.91	9067.91
Matte helmet versus youth jersey	7845	0.22	6793.97	1494.67	747.34	8592.34

Abbreviations: μ_s, coefficient of static friction; $F_\perp$, perpendicular force (N); f_s, total static friction force (N); $f_{s,helmet}$, portion of f_s experienced by the helmet (N); F_{Total}, total force experienced during the collision.

Table 5. Coefficients of Static Friction for Helmet-to-Helmet Combinations, Helmet-to-Jersey Number Combinations, and Helmet-to-Jersey Material Combinations

Combination	Mean ± SD
Glossy helmet versus glossy helmet	0.44 ± 0.10
Glossy helmet versus matte helmet	0.37 ± 0.04
Matte helmet versus matte helmet	0.27 ± 0.04
Glossy helmet versus stitched number	0.26 ± 0.01
Glossy helmet versus silkscreened number	1.14 ± 0.04
Glossy helmet versus sublimated number	0.32 ± 0.03
Matte helmet versus stitched number	0.25 ± 0.01
Matte helmet versus silkscreened number	0.85 ± 0.01
Matte helmet versus sublimated number	0.22 ± 0.03
Glossy helmet versus collegiate jersey	0.36 ± 0.01
Glossy helmet versus high school jersey	0.32 ± 0.00
Glossy helmet versus youth jersey	0.28 ± 0.01
Matte helmet versus collegiate jersey	0.28 ± 0.01
Matte helmet versus high school jersey	0.26 ± 0.01
Matte helmet versus youth jersey	0.22 ± 0.01

between helmet and football uniform materials. However, to enhance clinical relevance, we converted μ_s to force.

The helmet-to-helmet combination with the highest μ_s was the glossy helmet versus glossy helmet finish. Conversely, the matte helmet versus matte helmet finish resulted in the lowest μ_s (Table 5). The difference between the highest and lowest μ_s values between helmet finishes was 0.17 ($P = .013$), which could result in a difference of 611.45 N of force transmitted to the body. For the purposes of illustration, these calculations were based on a maximum football collision of 7845 N at a 60° angle. In this scenario, if all helmet finishes are matte, then a reduction of more than 600 N during high-force collisions is possible.

The helmet-to-jersey material combination with the highest μ_s was the glossy helmet versus collegiate jersey material. The lowest coefficient of friction was measured between the matte helmet and the youth jersey material (Table 5). This resulted in a difference of 0.14 ($P > .01$). At the same collision force and angle described earlier, this combination resulted in a difference of 475.57 N, meaning that a simple adjustment in helmet finish and jersey material could significantly reduce the forces transmitted to the body.

Finally, the highest μ_s (1.14 μ_s) was measured with the glossy helmet versus silkscreened jersey number (Table 5). The matte helmet versus sublimated numbers resulted in the lowest μ_s and a friction difference of 0.92 ($P < .01$). In this case, the difference between the highest and lowest friction combinations converted to the largest potential force attenuation of 3125.22 N. Because the lowest identified force resulting in neck failure was 3340 N,[3,5] these results suggest that lowering the μ_s between uniform materials could reduce forces by the same loads known to cause cervical spine injury. Conversely, high friction combinations could add damaging forces to a collision. Football collisions occur at many different forces and angles and, therefore, a variety of scenarios must be considered. The difference in forces as a result of different collision angles are illustrated in Figure 4.

Our results complement the work of Nightingale et al,[6] who demonstrated that a high-friction, padded surface resulted in more neck injuries than a low-friction, rigid surface. A low-friction padded surface may be ideal to not only allow for absorption of impact forces but also to allow the head to slide out of the pocket and avoid compressive forces from the oncoming player's torso. Our investigation took the work of Nightingale et al[6] a step further and

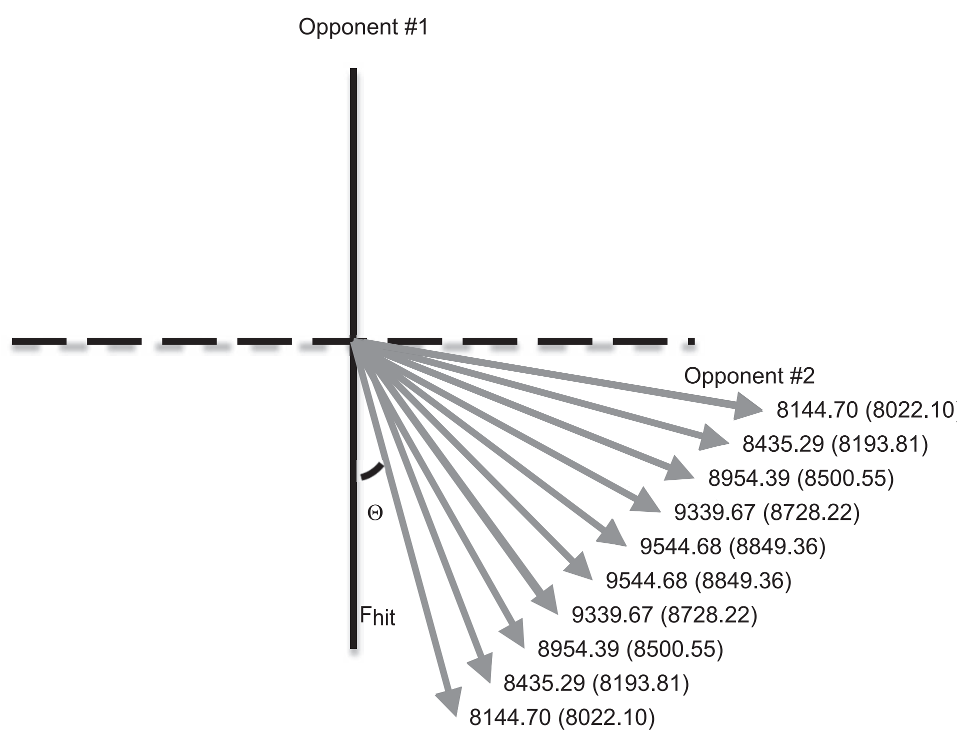

Figure 4. Comparison of the total amount of potential force resulting from collisions of 7845 N between a matte helmet versus matte helmet and glossy helmet versus glossy helmet (in parentheses) at the various testing angles. Abbreviations: Θ, angle of collision (°); F_{hit}, estimated force of a collision.

identified differences in friction between commonly used helmet and jersey materials. It seems logical to consider certain uniform materials and perhaps protective equipment as potential contributors to the high forces experienced by the body during football collisions.

Limitations

As in previous research, the modeling of forces is not without limitations. It is important to note that we did not model the natural attenuation of force caused by protective padding, muscle contraction, or intervertebral disc compression in these calculations. Regardless, the relationship between friction and force remains the same. When the helmet contacts another helmet or jersey, greater static friction will prevent the head from sliding off the opposing surface, thereby increasing the time the cervical spine is exposed to potentially damaging forces.

CONCLUSIONS

The forces produced by high-friction surfaces translated to nearly the same amount of force that Swartz et al[5] showed caused neck failure. Although most collisions in sport do not result in injury, it is prudent to reduce risk where possible. Our results may initiate discussions regarding uniform materials and spawn further inquiry in this area. Future researchers could enhance this work by testing a wider variety of helmets and jersey materials in more practical and natural environmental conditions (hot, humid, wet, etc).

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Address correspondence to Anthony M. Rossi, MSc, Athletic Training, Adrian College, 110 South Madison Street, Adrian, MI 49221. Address e-mail to arossi@adrian.edu.