

Assessing Head Impact Reduction Through Under-Mat Systems: A Fall Simulation Study of  
Ippon-Seoi-Nage and Osoto-Gari in Judoka

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## Abstract

Concussion rates are increasing in the sport of Judo. Most research on prevention focuses on how athletes respond to throws or the types of protective equipment they use to reduce impacts to the head and body. There is, however, a lack of research on the effectiveness of Judo mats in minimizing the risk of concussion during falls. In response to this research need, the proposed study explored the material properties of Judo under-mat systems by measuring their energy absorption through static testing. It also examined how different under-mat systems mitigate impact force, reduce acceleration, and lower the risk of head injuries during simulated dynamic falls in Judoka. Specifically, the study simulated scenarios when an athlete lands on the mat after being thrown with the Osoto-Gari technique and when an athlete hits the head on the mat while being thrown with the Ippon-Seoi-Nage technique. Four under-mat systems commonly seen in Judo training centers in Ontario were examined: a Judo mat with no under-mat, a pool noodle under-mat, a hockey puck under-mat, and an insulation under-mat system.

Descriptive statistics, including means and standard deviations, were computed, and inferential statistical analyses were performed utilizing mixed factorial ANOVAs to address the purpose of this study. The static testing results showed that the pool noodles and hockey pucks absorbed less energy than the baseline under-mat system, but they may provide more cushioning for athletes during falls. The dynamic simulations and human participant testing revealed that the pool noodle and hockey puck under-mat systems seemed to better mitigate the risk of concussion based on measures of force, linear and angular acceleration during the simulation of Osoto-Gari and Ippon-Seoi-Nage Judo techniques. The outcome of this study provides an avenue to assess the effectiveness of Judo under-mat systems in training centers to prevent concussion risk.

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## List of Abbreviations

AGSI	Angular Gadd Severity Index
AMTI	American Mechanical Technology Incorporated
ASDH	Acute Subdural Hematoma
ATD	Anthropomorphic Test Device
CT	Computed Tomography
HIC	Head Injury Criterion
IJF	International Judo Federation
NOCSAE®	National Operating Committee on Standards for Athletic Equipment
SRC	Sports Related Concussion
SIS	Second Impact Syndrome
TBI	Traumatic Brain Injuries

## Chapter 1 - Introduction

Judo concussion rates have increased dramatically throughout the world (Koshida et al., 2017b). Osoto-Gari and Ippon-Seoi-Nage, which are often the first Judo throw techniques taught to beginners, have been shown to have the highest risks of sport-related concussions (SRC) associated with improper performance of these techniques (Kamitani et al., 2013; Rukasz et al., 2011) and a lack of head protection. Although there is not one single definition of concussion, for the context of this study, a concussion is defined as a disturbance of neurological brain functions that results from biomechanical forces causing injury to the brain (Davis et al., 2023; Kazl & Torres, 2019; Meaney & Smith, 2011; Mullally, 2017; Wicklun et al., 2021).

Studies have shown an increase in the incidence of concussions for high school students who participate in high contact sports such as Judo and football. Thus, the neurological effects of SRC pose a concern, especially for young and inexperienced athletes. With the growing awareness of SRC and the increasing popularity of Judo, further research regarding injury prevention in the sport is critical.

Various prevention strategies have been investigated for Judo head injuries, all of which fall under two categories including prevention through training and prevention via athletes wearing protective equipment. Prevention through training focuses on athletes learning and acquiring skills on safe techniques for throws while practicing the sport. Breakfalls, for example, are taught as the safest way for athletes to fall (Kanō, 1994). The effectiveness of these safety techniques is assessed in most Judo studies using a kinematics analysis approach. Prevention with the use of additional athletic equipment, on the other hand, includes the development of specific head and neck suppression gear (Kamitani et al., 2018). Unfortunately, in the sport of Judo, athletes do not wear a gear for head protection, and some of these athletes are novice or unskilled to implement safe ways of falling to minimize the risk of head injuries. These two

categories, however, neglect to investigate the influence of Judo mats in minimizing the risk of concussion within the field of play in Judo.

The field of play in Judo is an 8 meter (m) by 8 m section of mats. These types of mats are regulated by the International Judo Federation (IJF). Many Judo clubs use an under-mat system between the floor and the Judo mats to provide additional shock absorption and cushioning to athletes when falling (Murayama et al., 2013). Minimal research has been done, however, to investigate the effectiveness of these under-mat systems implemented in many Judo clubs, especially since they are not regulated or mandatory.

Only two studies (Murayama et al., 2013, 2014) have acknowledged under-mat systems in Judo, but no conclusion has been reached regarding the effectiveness of these systems based on their material properties. The research to date has found that under-mat systems minimize SRC risk for linear impact accelerations known to cause concussions and skull fractures, but information regarding rotational impact accelerations, also known to cause concussions, remains unclear (Murayama et al., 2014). Furthermore, there is a need for additional research to examine the effectiveness of different under-mat system configurations in minimizing linear and rotational accelerations, and consequently the risk of concussion at front and back locations of the head, which are considered the most common impact locations during a Judo throw.

The present study aimed to address this research gap by systematically assessing how different under-mat material configurations influence the impact force, linear and rotational accelerations, as well as risk of head injury based on measures of Head Injury Criteria (HIC) and Angular Gadd Severity Index (AGSI) during simulated Judo falls, specifically focusing on the Ippon-Seoi-Nage and Osoto-Gari throwing techniques.

Static material testing, controlled dynamic simulations, and human participant Judo throws were conducted to address the purpose of this study. The static testing revealed that the baseline (M=30.4%) and insulation (M=30.7%) absorbed higher percentages of energy than the hockey pucks (M=20.3%) and pool noodle (M=19.8%). More energy absorption for the same amount of deformation during the static compression test suggested that the baseline and insulation had stiffer material properties and consequently a shorter time to hold that energy during a dynamic collision, resulting in more energy being transferred to the human, increasing the risk of head injury. The dynamic testing revealed that the pool noodle and hockey pucks provided more cushioning to the head impact for measures of linear and rotational accelerations, minimizing concussion risk during the controlled dynamic simulations for the Osoto-Gari (back-of-head impacts) and Ippon-Seoi-Nage (front-of-head impacts) simulated Judo throws. Similar outcomes were found during the human participant with the pool noodle and hockey pucks absorbing more force than the baseline for simulated Osoto-Gari Judo throws.

The findings of the current study not only enhance the understanding of the influence of specific Judo throw types on the risk of head injury but also provide a practical strategy for Judo clubs to implement safer training environments.

## Chapter 2 – Literature Review

### Judo

Judo is a Japanese martial art known as the ‘gentle way’ that focuses on maximum efficiency in all aspects of the sport, including both body and mind development while training for attacks and defence (Kanō, 1994). Judo is often seen in the Olympics as a specialized standing and ground fighting sport (Kanō, 1994; Pocecco et al., 2013). In Judo, there are two athletes competing against one another. Each athlete must attempt various techniques to obtain points. Whoever obtains a full point first wins the match. The sport utilizes throws, which are the standing techniques that force one athlete to fall to the ground. Throws create an opportunity for ground fighting to occur, where athletes then attempt to score points by controlling one another’s movements and keeping their opponent’s back on the mat (Kanō, 1994). In all techniques, there is a tori (one who “picks”) and a uki (one who “receives”). The tori are the person who initiates the technique and preforms it on the other athlete (Kanō, 1994). Whereas the uki is the athlete that the technique is done to (Kanō, 1994). Typically, the uki is the athlete who falls to the ground due to a throwing technique or is the athlete with the back on the mat during ground fighting. However, both athletes train both standing and ground fighting equally in preparation for competition.

Both standing and ground fighting experiences are two forms of training described by Kanō (1994) that target different aspects of the body and mind. The first form referred as Kata is a training that relies on the progression of forms and the fundamentals of each fighting technique. Kata targets muscle memory and attention to detail. It also promotes patience of the mind while building the required physical abilities such as muscle strength and flexibility (Kanō, 1994). The second form referred to as randori is a training that mimics an actual match with free

movement. Randori targets skill and form application. During this form of training, thoughtfulness, quick thinking, and intent are developed by the mind. The physical component in this form allows for muscular endurance and reaction times to be trained in the athlete (Kanō, 1994).

Given the large physical component of the sport, high-intensity training, accuracy, strength, velocity, and power are required for athletes to be successful (Franchini et al., 2011). With the ability of the sport to target all aspects of physical fitness, Judo is often taught in schools, recreational facilities, and gyms (Murayama et al., 2013). Kanō (1994) described the goal of training in an educational stance as the development of overall body strength while building mental and moral character. Thus, educational institutes such as high schools and universities promote Judo as a common program provided. Despite the sport's growing popularity since the early 1990s, the number of injuries, including concussion rates, has increased dramatically (Koshida et al., 2017b). The throws completed during standing fighting are the most common reason for injuries, although certain throws are associated with more injuries than others.

## **Judo Injuries**

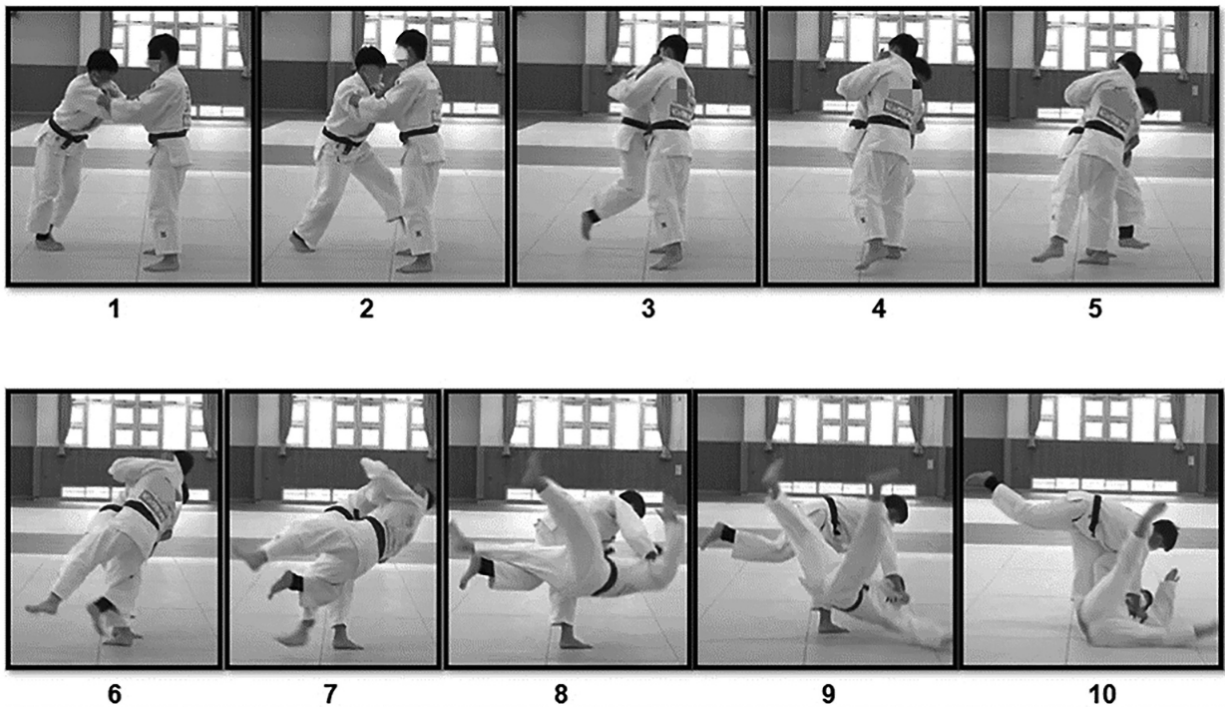
### ***High Injury Risk Throws***

**Osoto-Gari.** Osoto-Gari is commonly reported as the throw that causes injury to the uki more often (Murayama et al., 2014). The throw is completed when the uki falls backwards onto the mat. Osoto-Gari involves the tori loading the weight of the uki onto one foot by slightly pushing the athlete in the direction of the foot (Kanō, 1994). This pushing action causes the uki to shift the bodyweight onto the leg that the tori intends to hook. Without warning, the tori uses their leg to hook the outside of the uki's leg and pulls it out from under them (Kanō, 1994; see

Figure 1). The sudden pull of the leg often prevents the uki from preparing for the fall (Murayama et al., 2014). This lack of preparation occurs for both black belts (experts) and white belts (beginners).

### Figure 1

#### *Osoto-Gari Progression*



*Note.* Image taken from Liu et al., 2021.

However, when investigating the difference between Osoto-Gari completed by 12 male black belts and 10 male white belts, significant differences were seen in the angular momentums and velocities generated of the black belts (Liu et al., 2021). Using three-dimensional marker trajectory data taken from the tori with a 14-camera Mac3D motion analysis system©, Liu et al. (2021) determined that while completing Osoto-Gari, the tori generated a significantly greater peak angular momentum in the trunk and leg of the uki to complete the throw. Momentum was used in this study as an indicator of the throw's effectiveness. This angular momentum caused

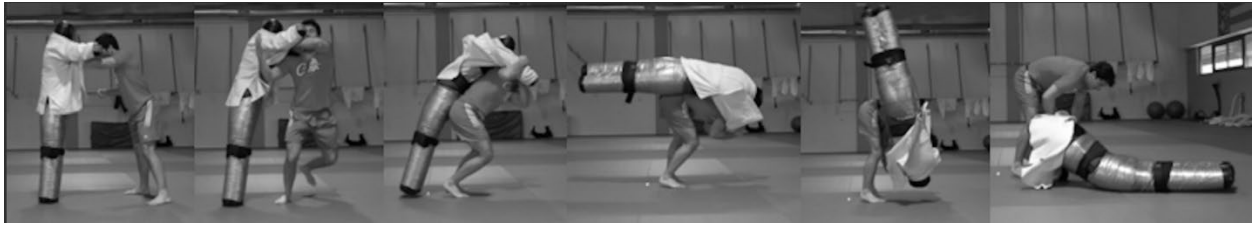
greater rotation in the uki, which resulted in the uki's fall. A contributing factor to this generated momentum was the peak velocities of the upper and lower body of the tori. The study found that experts had significantly lower angular velocity in the upper body but significantly greater in the lower body. The combination of the velocities determined the effectiveness of the throw. Given these findings, it is important to consider how the momentum generated from the velocity of the tori affects SRC risk of the uki.

As such, Murayama et al. (2014) investigated the head rotational acceleration that occurs when Osoto-Gari is completed. A series of simulations were completed using an anthropomorphic device (ATD) that was thrown by a Judo expert (fifth-degree black belt). The throw was performed onto the mat and the ATD instrumented with a triaxial accelerometer, recorded the head acceleration during the fall and impact. The reported peak resultant angular acceleration was between 4284.2 and 5525.9  $\text{rads/s}^2$  after four throws (Murayama et al., 2014), which was around the suggested concussion threshold proposed by Ommaya et al. (2002).

**Ippon-Seoi-Nage.** Injury reports are also high for both the tori and the uki during Ippon-Seoi-Nage throws, with an increased risk of head injuries particularly for the tori (Rukasz et al., 2011). When Ippon-Seoi-Nage is initiated, one of the tori's arms is placed in the opposite armpit of the uki while the tori's other arm maintains a hold on the sleeve of the uki (Kanō, 1994). The tori would have their back against the uki's trunk to pick up the athlete from this position (Kanō, 1994). The throw would occur when the uki falls over the tori as if completing a summersault, which poses a risk of head impact for the tori and uki as seen in Figure 2.

## Figure 2

### *Ippon-Seoi-Nage Progression*



*Note.* Image taken from Almeida et al., 2018.

In a self-reported survey given to athletes from five different international-level competitions, 53.8% of the injuries during Ippon-Seoi-Nage reported that the tori sustained the injury (Rukasz et al., 2011). In these reports, 80% of the injuries occurred during competition, which may be a result of the fatigue effect noted by Cetinić et al. (2022). A total of 30 Judokas with a mean age of 17.02 (SD=0.91) completed three throws before and after a fatigue protocol, which included 10 rounds of a 10 m shuttle run followed by two push-ups. A significant decrease in shoulder angle, pelvis height, hand velocity, and head position of the tori was seen during a repeated measures study of Ippon-Seoi-Nage (Cetinić et al., 2022). The decreased values of the kinematic variables may be reflective of how the effect of fatigue in high-intensity competition increases injury risk and more specifically head and neck injuries when performing Ippon-Seoi-Nage.

### ***Head and Neck Injuries***

Between 2003 and 2010, 72 Judo-related injuries were reported in Japan hospitals (Kamitani et al., 2013). Of those reported injuries, there were a total of 30 cases that were due to a head injury and 19 that were related to a neck injury, all of which occurred on the mat (Kamitani et al., 2013). Reports have shown that 30% of these injuries occurred in athletes under

20 years of age (Kamitani et al., 2013), similar to the findings of Murayama et al. (2013), who noted that SRC is most common in teens and young adults.

Neck strength has been identified as a contributing factor to SRC. Two studies investigated neck strength in Judo athletes as a cause of these injuries. The first study investigated neck flexion strength for 21 male novice athletes with 10 Judo training sessions and reported a mean peak neck flexion strength of 125.3 N (Koshida et al., 2017a). The second study investigated neck extension strength in expert Judo athletes. The researchers found that Judo athletes with mean years of Judo experience of 8.5 years were strongest at 126 degrees of neck extension and had an average neck extension strength of approximately 350 N (Tsuyama et al., 2001). Although the two studies focused on different forms of neck strength levels, the difference between novice athletes and experts seen between the two studies indicated that SRC in novice Judo athletes may be a result of minimally developed neck strength. When investigating the risk of head injuries related to unpreparedness between novice and expert Judoka, cervical muscle contraction speed was proposed as an additional factor due to the higher SRC in novices (Hironori et al., 2023). Significant differences in head acceleration in junior high school novice athletes and expert athletes were seen when an unexpected force of 1094 N at 200 mm/s was applied to the uki, but no significant differences were seen in the older groups (Hironori et al., 2023). This outcome suggests that a concussion seems to be more prominent among novice uki Judo athletes.

### **Concussion**

A concussion can be described as a disturbance of neurological functions that results from biomechanical forces causing injury to the brain (Kazi & Torres, 2019; Meaney & Smith, 2011; Mullally, 2017; Wicklund et al., 2021). Typically, concussions are classified as

acceleration-deceleration injuries, given that common cases of this injury result from a combination of magnitude, speed, and direction of the head ( Kazl & Torres, 2019; Wicklund et al., 2021). Concussions can occur whether or not there is a head impact. The cause of concussion can be a result of contact forces or inertial forces, both of which may involve a strike to the head. However, inertial forces are the impulsive head motions seen both with and without a strike to the head (Davis et al., 2023; Meaney & Smith, 2011). Sudden jerks to the head, commonly known as “whiplash,” are a prime example of the inertial forces that can cause a concussion. A secondary form of inertial force is rotational acceleration. During this form of concussion, a shear force occurs within the brain, causing tissue damage (Davis et al, 2023; Meaney & Smith, 2011), which may further affect the neurological functions of the brain. These forces cause an energy transfer in the brain through the acceleration-deceleration process.

Neurological disruptions, such as axon depolarization caused by energy transfers, lead to decreased function of both the axon and the neural network. This reduction in function results in symptoms associated with concussions, which are used for diagnosis (Kazl & Torres, 2019; Wicklund et al, 2021). Common symptoms include nausea, headaches, memory disturbances, and balance problems, all of which often play a key role in diagnosing a concussion. However, not all symptoms are the same in each case. Head injuries are extremely individualized, and severity will be dependent on the individual and mechanism of injury. Some symptoms, such as loss of consciousness, are indicative of a more severe concussion risk. As such, cerebral imaging with computed tomography (CT) and magnetic resonance imaging is beneficial in determining the incidence rate of TBI (traumatic brain injuries) and concussions (Mullally, 2017).

### *The Incidence Rate of Concussions*

SRC accounts for 45% of TBI in youth (Kriz & Roberts, 2021) since concussions are the mildest form of TBI ( Davis et al, 2023; Mullally, 2017). It has been reported that there are approximately 1.6 million cases of TBI a year in the United States alone reported by the Centers for Disease Control and Prevention (Mullally, 2017). Of that 1.6 million, over 300,000 reported cases yearly are from combat sports alone (Thunnaan et al., 2018). The high incidence rate of TBI indicates that the impact injury threshold is often reached. The impact threshold determining the degree of TBI is discussed throughout the literature. Broglio et al. (2010), described the theoretical concussion threshold to be achieved when head impact was observed at or above 70 g. A g is a unit of acceleration due to gravity. SRC was also reported when the head impact occurred at or above 4500 rads/s<sup>2</sup> of head rotation (Ommaya et al., 2002), where rads/s<sup>2</sup> is a unit of angular acceleration. Even with these reported thresholds, Dhote et al. (2022), found that SRCs are often hidden from authority figures and remain unreported due to fear of not being allowed to play. Due to this underreporting of concussions, it can only be inferred that these thresholds are more frequently reached. These under-reported concussions pose a concern due to neurometabolic disturbances in the brain, which increase the risk of long-term implications and well-being of the athlete (Davis et al., 2023; Dhote et al., 2022; Tsushima et al., 2018). The incident rate of concussion is also associated with the level of neck strength of the athlete.

Higher neck strength has been shown to decrease concussion risk. When comparing the neck strength of 6704 high school athletes' neck strength to the concussion rates seen during one academic year of play, concussion rates of those with a higher neck strength were significantly less than those with lower neck strengths (Collins et al., 2014). This study was in line with similar studies such as Eckner et al. (2014), who found that high neck strength was able to

stabilize the head when mechanical forces are applied. In 46 healthy athletes who participated in contact sports (i.e., soccer, ice hockey, football, martial arts, wrestling, and lacrosse), greater isometric neck strength was significant in decreasing impulsive loads in all planes of motion (Eckner et al., 2014). It was proposed that the anticipation of impact also minimized injury risk during testing. Further research on the effect of anticipation effect was proposed, especially in cases where repetitive impacts occur leading to multiple concussions and second impact syndrome (SIS) while practicing the sport.

### ***Concerns Associated with Multiple Concussions***

Recent studies aim to determine the link between the neurometabolic disturbances and the risk for developing post-concussion symptoms. These long-term implications had various theorized causes. SIS was one of the most hypothesized and discussed theories that explain why there are long-term effects from SRC (Cantu, 2016; Quintana, 2016). SIS is when a second head injury occurs before the brain is fully recovered from an initial SRC (Cobb & Battin, 2004). SIS is different from SRC due to the possible rapid onset swelling and herniation of the brain potentially resulting in death (Cobb et al., 2016). SIS lowers the concussion threshold after each TBI, (Cantu, 2016; Quintana, 2016), and by doing so, the synergistic effect of these injuries results in a greater overall effect that is more severe than the respective injuries (Webbe & Barth, 2003). SIS has been seen in adults but is most common in those under 18 years of age and has been hypothesized to limit the brain's ability to regulate cerebral pressure (Cantu, 2016; Quintana, 2016).

In 2018, the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) was used by Tsushima et al. (2018), to investigate the effect of SIS on the difference in scores between high school athletes in high-contact sports such as football, where multiple impacts to

the head are more frequent, and low-impact sports including soccer, basketball, and baseball. Although this study did not include Judo, the study compared test scores from groups of 20 students after one season of play, and found that there were significantly poorer scores in visual motor speed and reaction time reported in the high-contact sports group than those in low-contact sports (Tsushima et al., 2018). Former athletes who participated in contact sports such as wrestling and football have been shown to have high rates of depression and reduced cognitive abilities due to a history of multiple SRC (Kerr et al., 2014), which also occurs in Judo. These effects were a result of the chronic brain damage that occurred during the former athlete's time in sport and can even result in progressive neurological disorders and behavioural responses (Dhote et al., 2022; Kerr et al., 2014; Mullally, 2017). These changes in test scores and behaviour supported the theory that multiple impacts and SIS are indicators of long-term neurological effects, which can also be found in Judo athletes.

### ***Second Impact Syndrome in Judo***

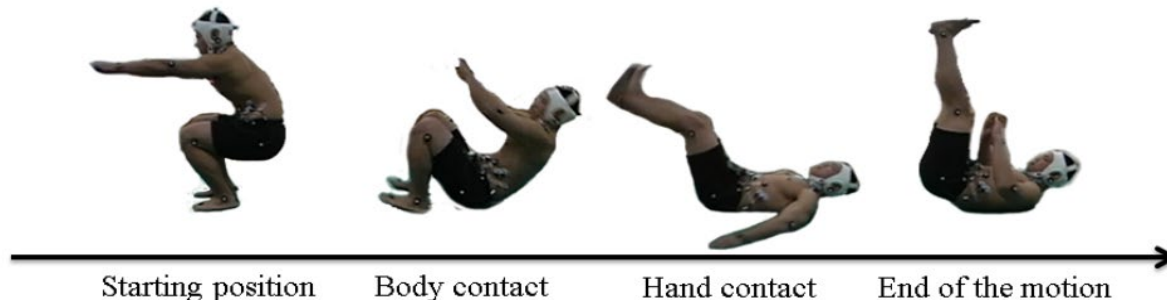
A case study from Japan of a 16-year-old youth who practiced Judo and experienced SIS reported that surgery after the second impact was required due to an acute subdural hematoma (ASDH; Yokota & Ida, 2016). The athlete had a total of 8 months of Judo training and received an impact to the occipital region of the head, which caused extensive concussion symptoms (Yokota & Ida, 2016). Three days post-impact, a head CT scan was completed at the hospital and reviewed (Yokota & Ida, 2016). The authors noted that the athlete was initially sent home, and after returning to sport nine days post-initial impact, a second impact occurred, resulting in a second hospital trip and a second CT scan, which then showed an ASDH so extreme that emergency surgery was required (Yokota & Ida, 2016). The case reported is consistent with many injuries often seen in Judo. The high incidence of SRC and ASDH reports posed concern

regarding the severity and incidence rates of injuries, and therefore, prevention strategies such as breakfall techniques, headgear protection, and the use of under-mat systems are needed to minimize the risk of concussions.

## **Injury Prevention**

### ***Breakfalls as Prevention***

A breakfall is a preventative measure that is learned rather than a piece of equipment given to athletes in Judo. Breakfalls have been described as the first technique taught to new students to mitigate the force applied to the uki after a throw (Hashimoto et al., 2015; Kanō, 1994). A breakfall is the proper way to fall on the mat that involves neck flexion to protect the head from impact (Kanō, 1994). Four different breakfall techniques are taught to Judokas including back, side, front, and rolling. The technique that is used depends on which direction the uki is falling. A back breakfall (see Figure 3) requires the uki to maintain neck flexion, whereas a front breakfall requires the uki to maintain neck extension. A side breakfall and rolling breakfall require a combination of neck flexion and lateral flexion (Koshida et al., 2017a). However, all breakfalls have three requirements to be successful. The first and most important is proper neck flexion or extension, which prevents and minimizes head impact with the Judo mat (tatami). The second is for the uki to ensure the last impact with the mat is the shoulders and head. This approach allows the initial impact force to be distributed throughout the body and minimizes the potential for head and neck injury (Koshida et al., 2017a). The final requirement is arm placement. That is, when impact occurs, the uki must slap the mat with their arm 45 degrees from their trunk to assist with force distribution through the body (Koshida et al., 2017a).

**Figure 3***The Stages of a Back Breakfall*

*Note.* Image taken from Koshida et al., 2014.

After being thrown with Osoto-Gari, a back breakfall can absorb the 204.82 N impulsive force that otherwise would be applied to the uki's head (Hashimoto et al., 2015) when the proper progression and preparation can occur. Hashimoto et al. (2015) quantified the distance travelled for each body segment of the uki when thrown with Osoto-Gari. When a breakfall is performed, the uki's trunk will travel a total fall distance of approximately 77% of its body height. The head, however, will travel 70% of the uki's body height before impact. This information aligns with the breakfall principles initially developed by Kanō (1994), which outlined the importance of the trunk contacting the mat before the shoulders and head, to mitigate the impact. The difference between these two points of contact is the distance the head travels before the impact (Koshida et al., 2017b).

Koshida et al. (2017b) investigated the ability to mitigate these forces. A comparison of breakfalls completed by experienced Judo athletes with at least seven years of competitive Judo and novice Judo athletes with a minimum of ten 90-minute Judo classes completed was conducted. The throws were carried out with Osoto-Gari by a Judo expert with a third-degree blackbelt and 20 years of experience (Koshida et al., 2017b). The experienced athletes exhibited

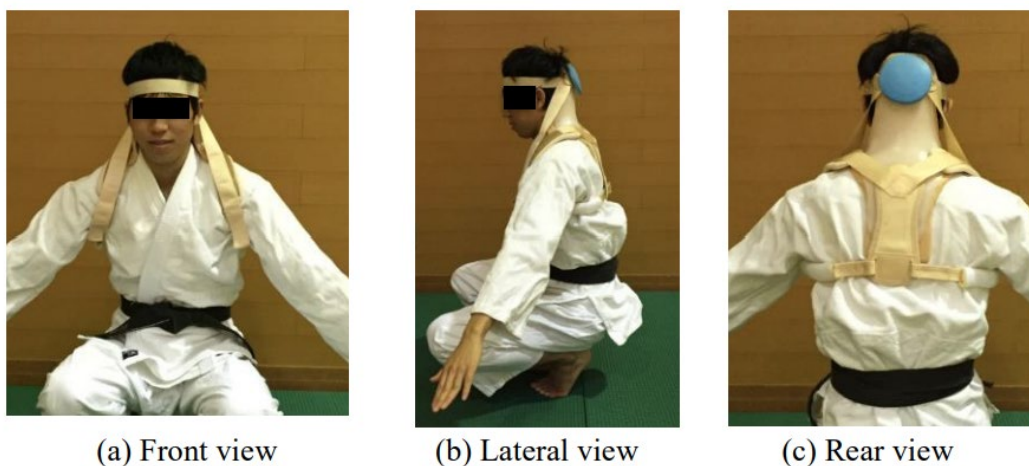
a significantly higher degree of neck flexion during the breakfall, which was hypothesized to result from the higher neck flexion strength. This outcome further supports the notion that neck strength may be essential to minimize SRC risk. However, studies have stressed that the motion of the neck does not occur in a single-plane (Koshida et al., 2017a).

### ***Head and Neck Gear***

To mitigate the movement of the neck in multiple planes of motion, Kamitani et al. (2018) developed a neck extension suppression system that new athletes would wear. The system involved a central support structure and shock-absorbing foam, as seen in Figure 4. The central support prevented neck extension and multiplane motion, while the shock absorber provided a barrier between the head and mat. Although there was a significant reduction in maximum neck angular velocity and head rebound angle, the device had many limitations, including the risk that protectors such as this may increase the amount of force placed on the joints, increasing the risk of injuries such as sprains instead of SRC (Kamitani et al., 2018). Headgear without a suppression system similar to wrestling headgear has also been investigated. However, given the allowance of chokes and ground fighting, this approach poses a greater risk to both the tori and uki (Kamitani et al., 2018). The other protection system used to mitigate the risk of head injury in the sport of Judo is the use of under-mats.

## Figure 4

*Proposed Neck Suppression System (Kamitani et al., 2018)*



*Note.* The frontal, lateral, and rear view of the investigated neck suppression system with a central support structure (seen as the thick light brown plastic along the cervical spine) and shock absorber (seen as the blue circle).

### ***Under-mat Systems***

Judo mats are regulated by the IJF and must adhere to certain material properties to ensure athlete safety. Additionally, the Judo mats are required to have a surface texture created through a rice-straw embossing pattern (see Figure 5), to prevent athletes from slipping on the mats. Then, to prevent the mats from slipping on the athletes, a gripping waffle pattern typically made of rubber is placed on the base of the Judo mat (see Figure 6). Judo mats need to be tested to obtain approval from the IJF. The mats must be drop tested with a critical fall height of 1.6 m and must be tested at multiple points to ensure homogeneity (European Committee for Standardization, 2001). The mat thickness must be within  $\pm 5$  mm, and thickness tolerances are typically  $\pm 3\%$  to obtain approval. As such, most mats are at a standard thickness of 40 mm and a density of  $240 \text{ kg/m}^3$  which creates a force reduction of approximately 75%. This force reduction

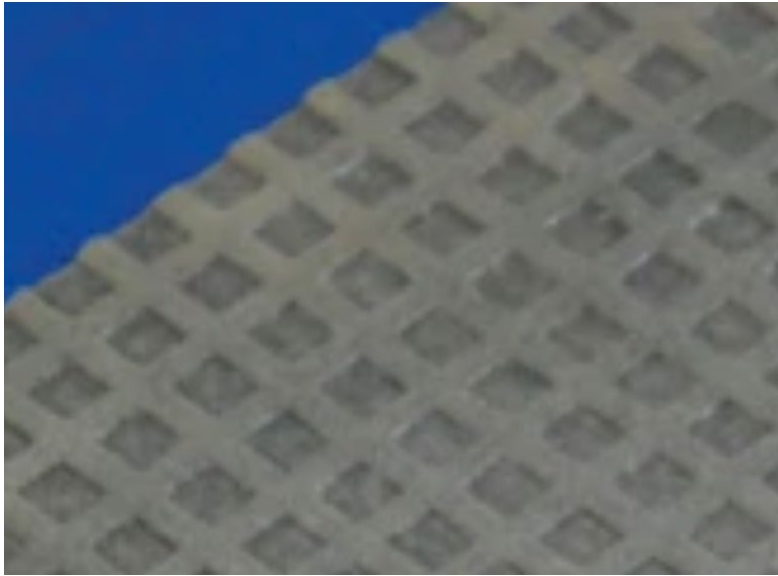
highlights the energy absorption capabilities of the Judo mat, given that energy absorption is defined as the process by which a material takes in, then dissipates energy from an external source (Xiao et al., 2022).

**Figure 5**

*Judo Mat Rice-Straw Pattern*



*Note.* Image taken from <https://www.hatashita.com/products/dax-tatami-mats>.

**Figure 6***Judo Mat Waffle Pattern*

*Note.* Image taken from <https://www.hatashita.com/products/dax-tatami-mats>.

When testing the material properties of the mats, quasi-static testing is a key element to determine how the mats behave under pressure. The slow application of force creates a stress-strain curve that shows how the Judo mat changes shape over time (Xiao et al., 2022), while also utilizing a controlled environment to focus more on the mats themselves. This deformation of the mat is the energy that the material absorbs (Xiao et al., 2022). Dynamic testing focuses on impact kinematics to determine injury risk. As previously mentioned, acceleration-deceleration injuries are a result from a combination of factors (Kazl & Torres, 2019; Wicklund et al., 2021), which all contribute to impact kinematics. By investigating how Judo mats behave from a combination of location of the impact, type of material, magnitude of the impact accelerations, velocity of the impact, and direction, researchers can then utilize tools such as the AGSI and HIC to make assumptions on injury risk from a practical component.

Only two studies (Murayama et al., 2013, 2014) were identified that investigated the effects of under-mat systems in judo, with the throw techniques being Osoto-Gari and Ouchi-Gari. Murayama et al. (2013), which examined the effect of an under-mat system on the impact forces induced to the head after being thrown with two of the most common Judo throws (Osoto-Gari and Ouchi-Gari). The team investigated if the implementation of a 60 mm thick synthetic sponge made of urethane and polyethylene placed under a standard tatami Judo mat would alter the impact forces to the head during Osoto-Gari and Ouchi-Gari. The Ouchi-Gari technique, is another standard Judo throw that follows the same throw progression as Osoto-Gari. The only difference between Osoto-Gari and Ouchi-Gari throwing techniques is which leg the tori hooks to pull out from under the uki. During Ouchi-Gari, the tori hooks between the uki's legs. Thus, when facing each other, the tori's leg will hook and pull out the uki's leg that is directly in front of them. These throws were completed on an ATD, which was thrown by a fifth-degree black belt Judo expert four times, with each throw mat condition (Murayama et al., 2013). The researchers collected head linear acceleration with a tri-axial accelerometer in all three planes of motion (longitudinal, lateral, and vertical) to determine the resultant acceleration of the uki. The resultant linear acceleration was calculated using Equation 1, and the peak acceleration was described as the maximum value that occurred for an impact speed of at least 3 m/s.

$$Gr = (Gx^2 + Gy^2 + Gz^2)^{1/2} \quad (1)$$

where:

$G_r$  = resultant linear acceleration;

$G_x$  = linear acceleration in the X axis;

$G_y$  = linear acceleration in the Y axis; and

$G_z$  = linear acceleration in the Z axis.

Head acceleration during Osoto-Gari was reported between 51.6 g and 79.9 g without an under-mat system, then decreased to between 36.1 g and 45.7 g with the system (Murayama et al., 2013). Murayama et al. (2013) found that adding the under-mat system ensured that head movement was further from the proposed SRC threshold of 70 g by Broglio et al. (2010).

The study also implemented the head injury criterion (HIC), a tool commonly used to evaluate head injury in sports during collisions (Murayama et al., 2013). HIC uses head acceleration and duration to predict the likelihood of injury as well as the severity of injury (Hutchinson et al., 1998). Higher HIC values indicate a greater probability of severe head injury. Murayama et al. (2013) calculated HIC using the following expression:

$$HIC = \left\{ (t_2 - t_1) \left[ \frac{1}{t_1 - t_2} \int_{t_1}^{t_2} a(t) dt \right]_{max}^{2.5} \right\} \quad (2)$$

where:

$t_1$  = initial time in seconds;

$t_2$  = final time in seconds;

$a(t)$  = instantaneous resultant linear acceleration, in g;  $a(t)$

is

the  $G_r$  of Equation 1; and the exponent 2.5 acts as a weighting factor that increases the sensitivity of the HIC to higher accelerations, allowing better discrimination between low- and high-severity impacts.

Based on Murayama et al. (2013),  $t_1$  and  $t_2$  are any two arbitrary time points during the acceleration pulse not to be more than 15 ms apart or  $t_2 \leq t_1 + 15$  ms. Murayama et al. (2013) found that the HIC values for Osoto-Gari significantly decreased with the under-mat system.

However, the second study completed by Murayama et al. (2014) noted that rotational acceleration was not effectively reduced with the addition of the system. Rotational acceleration was calculated using Equation 3 to determine resultant angular acceleration; however, both studies are limited by the minimal number of participants used during testing.

While these researchers did not measure rotational acceleration and risk of head injury due to rotational acceleration, other researchers had provided an avenue to measure rotational acceleration and the corresponding risk of head injury using Equations 3 and 4 (Rybak et al., 2021). These equations can be used to further assess the effectiveness of Judo mats. AGSI (angular Gadd severity index) of head injury was calculated in the present study using Equation 4 via MATLAB® software.

$$\alpha = \sqrt{(\alpha_x^2 + \alpha_y^2 + \alpha_z^2)} \quad (3)$$

where:

$\alpha_x$  = Angular acceleration about the X axis

$\alpha_y$  = Angular acceleration about the Y axis

$\alpha_z$  = Angular acceleration about the Z axis

and

$$AGSI = \int_0^T \left[ \frac{\alpha(t)}{88} \right]^{2.5} dt \quad (4)$$

where:

$\alpha(t)$  = instantaneous resultant angular acceleration of the head form, in

rads/s<sup>2</sup>,  $\alpha(t)$  is by Equation 3;

$T$  = impulse duration; and

88, in  $\text{rads/s}^2$  is a normalization constant.

The main issue, however, is that head injuries in Judo persist despite existing prevention strategies such as IJF-regulated headgear and breakfall techniques derived from Kanō's teachings. The recurrence of concussions indicates that these approaches may be insufficient, highlighting the need for alternative protective measures. While some studies have mentioned under-mat systems, no research has specifically examined their role in mitigating head impact forces, acceleration and energy, despite the lack of regulations governing the surfaces beneath tatami mats. This gap is significant because head impacts, especially from backward falls where the occipital lobe is most at risk, remain a critical mechanism of SRC. Therefore, research is needed to investigate how different under-mat systems, in combination with throwing techniques may reduce concussion risk in Judo athletes at different locations of the head.

## **Research Purpose**

This study examined if commonly used under-mat systems efficiently minimize the SRC risk of Judoka in both the uki and tori. The first purpose of this study was to examine the material properties of different under-mat systems by measuring their energy absorption capacity during static testing. The second purpose of the study was to analyze the force absorption capacity and reduction of risk of head injury of various under-mat systems during simulated free-fall dynamic head collisions when using two different Judo throwing techniques (Osoto-Gari and Ippon-Seoi-Nage). The third purpose was to examine which under-mat condition would absorb the most force as compared to the other under-mat conditions when a uki simulated dummy was thrown by a human with advanced-level Judoka.

The independent variables manipulated by the researcher were throw type (Osoto-Gari and Ippon-Seoi-Nage) and under-mat condition (no under-mat, pool noodle, hockey puck, and insulation). The dependent variables measured or computed by the researcher were energy absorption, impact force, linear acceleration, rotational acceleration, HIC, and AGSI. The following research questions and hypotheses guided this research.

## **Research Questions and Hypotheses**

First purpose:

- 1) Which under-mat system demonstrates higher energy absorption capacity when a load is applied to the mat during static testing?

The researcher hypothesized that the pool noodle under-mat condition would absorb the least energy when compared to the other under-mat conditions during static testing.

Second purpose:

- 2) Which under-mat system demonstrates larger impact force absorption capacity and minimizes linear and rotational accelerations during simulated free-fall dynamic head impacts of a tori and uki using the Osoto-Gari and Ippon-Seoi-Nage throwing techniques?

The researcher hypothesized that the pool noodle under-mat condition would absorb the most force, reduce the most linear and rotational accelerations during the impact when compared to the other under-mat conditions for both simulated Judo throwing techniques.

- 3) Which under-mat system minimizes risk of head injury as measured by the HIC and AGSI during simulated free-fall dynamic head impacts of a tori and uki using the Osoto-Gari and Ippon-Seoi-Nage throwing techniques?

The researcher hypothesized that the pool noodle under-mat condition would have the lowest risk of head injury as measured by HIC and AGSI, respectively, when compared to the other under-mat conditions for both simulated Judo throwing techniques.

Third purpose:

- 4) Which under-mat condition demonstrates larger head impact force absorption capacity of the uki simulated by a Fuji Standing Grappling Dummy when being thrown by a human tori using the Osoto-Gari technique with advanced-level Judoka?

The researcher hypothesized that the pool noodle under-mat condition would absorb the most force as compared to the other under-mat conditions when the uki simulated dummy was thrown by a human with advanced-level Judoka.

## Chapter 3 - Methodology

### Instruments

#### *Dax Tatami Judo Mats*

Dax tatami IJF-approved Judo mats (see Figure 7) were used for simulated dynamic head impact and human Judo throwing techniques. The mats were equipped with an E215 compound foam to achieve a 40 mm thickness (Dax Tatami Mats With Superior Shock Absorption, 2024). The E215 compound foam is typically lightweight, durable, and has energy return characteristics that make it ideal for absorbing impact and providing comfort. As such, the mats are marketed to have a force reduction of approximately 75% and a 420 kg/m<sup>3</sup> density. Dax tatami mats are the most used Judo mats in Ontario, Canada. For this study, the Dax tatami mats were used in combination with three under-mat system configurations, as seen in Figure 8 for both simulated dynamic head collisions and human participant throw testing.

#### **Figure 7**

#### *Dax Tatami Judo Mats*



*Note.* Image taken from <https://www.ezymats.com.au/Judo-tatami-mats/>.

### *Investigated Under-mat Systems*

The first under-mat system used in this study included a pool noodle configuration between the tatami mats and the flooring surface. This configuration is one of the most common setups in Judo training clubs, given that it is relatively low-cost. The King-brand jumbo pool noodles had an outside diameter of 6.1 centimetre (cm) and inside diameter of 2.5 cm. The pool noodles were cut into 3.8 cm thick doughnuts and glued to 1.2 cm thick spruce plywood. Four rows of five doughnuts with a 1.9 cm gap between each doughnut were configured as shown in Figure 6. The primary material in the pool noodles is high-density polyethylene, which has been shown to have a high level of strength and toughness while maintaining a low density, allowing it to absorb significant energy and experience reversible deformation (Marissen, 2011).

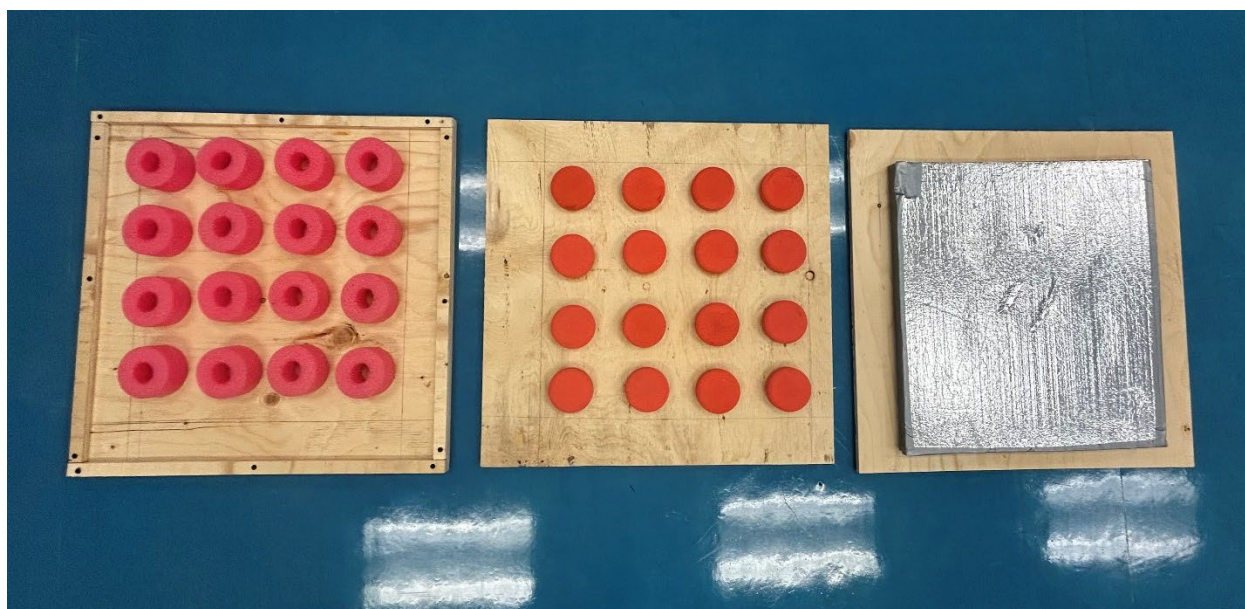
Polyethylene is often used as an under-padding or additional force absorber in protective equipment, such as helmets due to its energy-absorbing properties (Luo & Liang, 2017). The pool noodle under-mat system had an additional 2.5 cm in border along the edges of the plywood frame to account for the height of the pool noodles. The purpose of the boarder was to ensure mat stability, given that the pool noodles are taller than the other under-mat systems.

A second under-mat system composed of sponge hockey pucks was used in this study, as shown in Figure 8. The same set-up as the pool noodles and spruce plywood was used, but with Winnwell© Sponge Practice Hockey Pucks glued to the plywood. However, there was a 1.2 cm gap between each row of pucks, given the greater diameter of the pucks compared to the pool noodles. Each puck consisted of a 8 cm diameter and height of 2.5 cm of rubber. As such, there was a high level of durability and resilience with the pucks, given that the solid rubber material (Gent & Walter, 2006). This approach allows for a greater life span with this type of under-mat system than other systems.

The third under-mat system used in this study was an insulation under-mat system, as shown in Figure 8. This type of under-mat system is the least commonly used in Judo. For this under-mat system, a DuroSpan 2.5 cm rigid insulation panel was cut to the size of the wooden block system or force plate for its respective testing. Like the other systems, the foam insulation was glued to the spruce plywood. This type of under-mat system is unique because it is the only complete panel system. For the previously mentioned under-mat systems, however, each configuration involves areas without force absorption material.

### Figure 8

#### *Three Under-mat Systems*



*Note.* The system on the left was the pool noodle under-mat system. The additional border to account for the height difference can be seen with black screws along the edge of the plywood. The middle system was the hockey puck under-mat system, and the system on the right is the insulation under-mat.

Finally, the fourth under-mat configuration used in this study was the baseline with the tatami mats placed directly on the force plate. This approach mimicked some of the Judo club

configuration systems that placed the mats directly on the floor or concrete without an under-mat system.

***Chatillon TCD1100® Force Tester Instrumented with AMTI® Force Plate***

A Chatillon® TCD1100 Force Tester (see Figure 9) was used to collect the static data to examine the material properties of the under-mat systems. The Chatillon® TCD1100 is a force measurement instrument used to measure compressive (or tensile forces). The force tester is commonly used to apply a controlled load or controlled displacement to various materials in static testing. The force-deformation responses obtained from the device were used to determine energy absorption of each under-mat system material. The force-deformation response is defined as a change in dimension and shape due to the application of a force (Hall 2011). Compressive force is described as pressing or squeezing force directed axially through a body or structure (Hall 2011). Energy absorption is referred to as the process of dissipating the input energy from external loading due to the applied force and deformation of the material (Yu & Xue, 2022).

**Figure 9**

*Chatillon® TCD1100 Force Tester*



*Note:* Image taken from <https://www.ametektest.com/service-and-support/obsolete->

The under-mat system sample underwent 12.5 mm of compression with respect to its original form, for 15 trials or cycles. The force and compression data collected was used to create force and displacement plots for each under-mat sample to represent the loading and unloading of each material. The area enclosed by the loading and unloading curves of the force and displacement plots represented the energy absorption of each under-mat type.

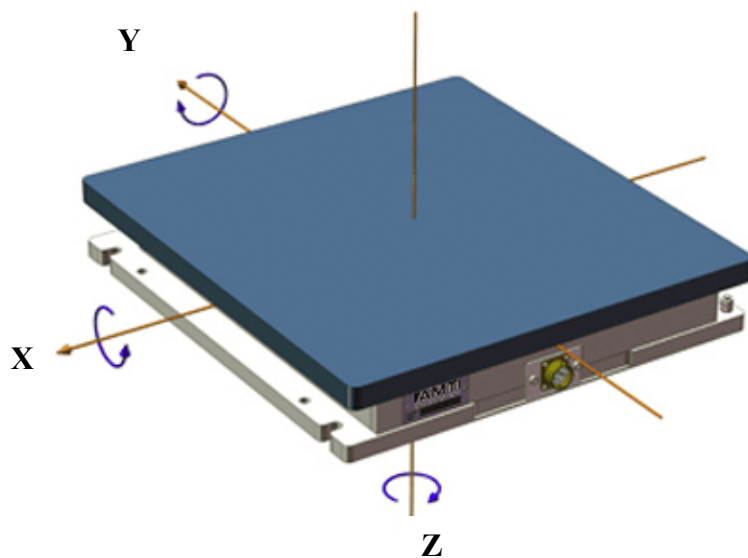
### ***American Mechanical Technology Incorporated Force Plate***

For this study, AMTI® force plates (see Figure 10) were used to collect the impact forces during the dynamic simulations and human participant testing. These devices are highly standardized instruments used for precise force measurement, allowing researchers to better understand how mechanisms of head injury occur and how humans respond to external forces (Beckham et al., 2014). These plates collect six key measurements including three forces and

three moments in the X, Y, and Z directions (Beckham et al., 2014). Moments around each axis represent the rotational forces applied to the plate (Beckham et al., 2014).

**Figure 10**

*American Mechanical Technology Incorporated Force Plate*



*Note.* Reprinted from Latelle et al. (2015).

In the case of human participant testing for the current study, the AMTI® force plates (see Figure 11), which is commonly used for gait testing in the School of Kinesiology at Lakehead University were utilized to collect the Fuji Dummy data. The force plate was fitted with each testing condition and served as the target for the human participant to throw the dummy. The impact forces of the dummy's head were in the X, Y, and Z directions, which were then used to calculate the resultant impact force.

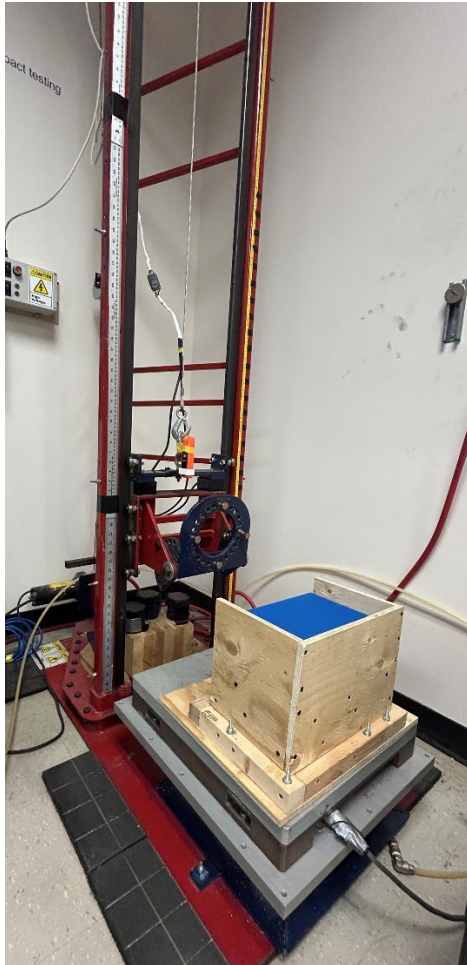
**Figure 11***AMTI® Force Plates for Human Participant Trials*

*Note.* Image taken from <https://summitmedsci.co.uk/2022/08/30/how-to-choose-the-correct-amti-force-plate-for-your-next-project/>.

***Lakehead University In-House Impact Drop System Instrumented with NOCSAE® Head Form, Hybrid III Neck and AMTI® Force Plate***

Lakehead University's in-house impact drop system (see Figure 12) was used for this study. The system was developed through a partnership between the School of Kinesiology and the Department of Mechanical Engineering. The drop system was fitted with a National Operating Committee on Standards for Athletic Equipment (NOCSAE®) head form and customized Hybrid III neck (see Figure 13). The NOCSAE® head form is an anatomically accurate model standardized for impact testing. The in-house system was developed as a dual rail system with a drop carriage that provides a mount for the head form. High-powered magnets connected to a controller and attached to a 110-volt AC winch were used to move the drop carriage to the desired testing height. When the magnets were demagnetized by pressing a button on the controller, the carriage free-fell until impact occurred with an AMTI® force plate placed at the base of the vertical impactor to collect the resultant impact force from the forces in the X,

Y, and Z directions. Carlson et al. (2016) provided evidence of reliability and validity for the use of the vertical impactor to measure impact acceleration and estimate the risk of head injury during a fall by comparing it to a standard, commercially available drop system instrumented with a NOCSAE® head form and mechanical neck. Carlson et al. (2016) found strong and significant correlations between both systems when measuring linear impact accelerations across helmet impact locations, providing evidence of concurrent validity for use of the in-house drop system. The front boss (ICC=.84) and the rear boss (ICC=.95) both indicated significant correlations between the different systems. Evidence of reliability of the system was also found with a degree of agreement value of  $r=.922$  ( $p < .005$ ,  $n=100$ ) after completing 100 drops for each of the four different locations (Carlson et al., 2016). Considering the evidence supporting the reliability and validity of the system, it has been utilized in various research projects aimed at studying the mechanisms of head injury. Additionally, it has been employed in research projects to evaluate the performance of helmets in the sports of hockey, lacrosse, football, and boxing, specifically in terms of reducing the risk of concussion during dynamic impact head collisions. (McGillivray et al., 2022; Pennock et al., 2021; Zerpa et al., 2017, 2021).

**Figure 12***Impact Drop System*

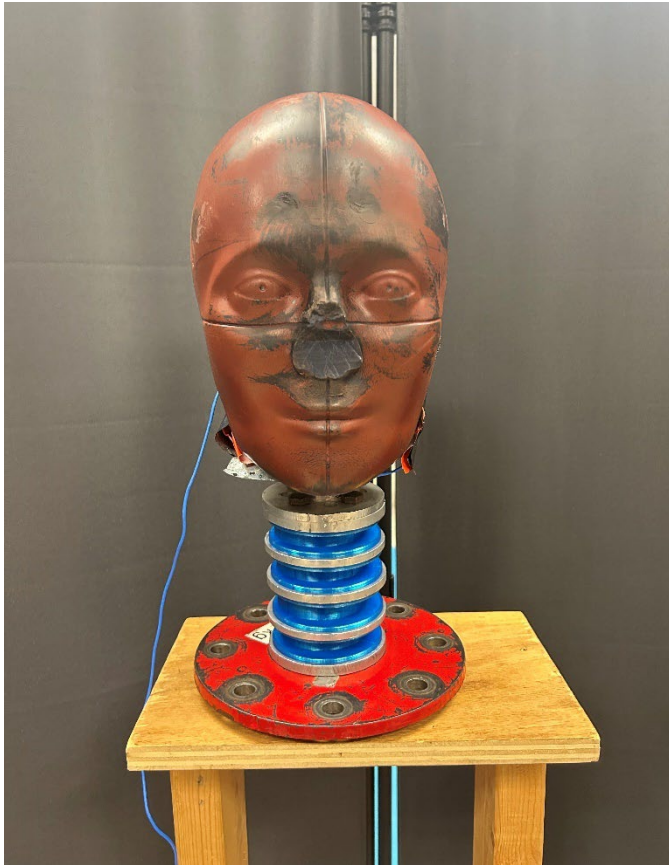
**NOCSAE® Head Form.** The system used a medium-sized NOCSAE® head form to simulate the 50<sup>th</sup> percentile of adult human heads. This head form has been typically used in concussion and head injury research in sports, given its durability and reliability (Mertz, 1985; NOCSAE®, 2025). For this study, the head form was instrumented with linear impact accelerometers to measure acceleration in the X (anterior-posterior), Y (superior-inferior), and Z (left-right) directions (MacAlister, 2013), which means that all three directions of motion provided insight into how a human head may behave in the real world during a head collision in

the sport of Judo. The linear accelerometers connected to a power supply, PCB model 482A04 Delsys Trigno® wireless magnetometers sensors were also attached to the top of the NOCSAE® head form to capture the angular displacements in the X, Y, and Z directions during each head impact (Delsys Inc., 2024; MacAlister, 2013). The linear acceleration and angular displacements measures were processed with a MATLAB® script to align the frequency of the linear and angular sensors, filter the noise using cubic splines and compute the resultant linear and rotational acceleration, as well as the risk of injury as measured by HIC and AGSI.

**Hybrid III Neck.** The hybrid neck form was designed to mimic the 50<sup>th</sup> percentile of a human neck (Spittle et al., 1992). For the current study, the mechanical neck was composed of a series of steel discs and in-house 3D-printed cervical vertebrae to simulate the movements of a human neck and mimic neck strength through a center cable torqued to the desired human neck strength. Pennock et al. (2018) described the value of the adjustable torque as having the ability to increase or decrease neck compliance to consistently mimic human neck muscle strength. The layers of simulated cervical spine vertebrae are seen in Figure 13.

**Figure 13**

*NOCSAE® Head and Hybrid Neck Form*



### ***Fuji Standing Grappling Dummy***

A Fuji Standing Grappling Dummy (see Figure 14) was used for dynamic testing to simulate a uki being thrown by a human tori in the sport of Judo. The 6-foot-tall standing dummy was filled with pool noodles, play sand, and a foam mattress topper. Standard pool noodles were cut into various lengths, then filled with Quikrete© brand play sand and sealed with duct tape. This approach added weight and structure to the dummy to mimic how it felt to throw a uki. However, full-sized pool noodles with the same set-up as the cut ones were used in the legs to provide more structure. To fill in the space between the pool noodles, a queen-sized polyurethane

foam mattress topper from the Red Label Walmart© brand was cut and stuffed into the dummy. A total of 10 pool noodles and one mattress topper were used to fill the dummy until the canvas shell was stiff.

### **Figure 14**

*6-foot-tall Fuji Grappling Dummy*



*Note.* Image taken from [https://www.hatashita.com/products/fuji-grappling-dummy-standing?\\_pos=2&\\_psq=grappling&\\_ss=e&\\_v=1.0](https://www.hatashita.com/products/fuji-grappling-dummy-standing?_pos=2&_psq=grappling&_ss=e&_v=1.0).

### ***PowerLab® Hardware, MATLAB®, SPSS®, and LabChart® Software***

PowerLab® hardware and LabChart® software were used to record the data in real time and process the information from all the force, accelerometer and magnetometer sensors used in this study with sampling rate of 20 kHz. A MATLAB® (The Mathworks Inc., 2025) script was used to collect the vertical and displacement data to compute the energy absorption capabilities

of each under-mat systems during static testing. Another MATLAB® script was used to compute the resultant forces, resultant linear and rotational accelerations, and risk of head injury indices as measured by HIC and AGSI. This information was used to evaluate the protective capabilities of different under-mat systems in minimizing the risk of concussion during dynamic testing (Silvestros et al., 2024). Finally, the SPSS® statistical package was used to conduct descriptive and inferential statistical analyses to address each of the research questions.

## **Procedures**

### ***Static Material Testing***

The researcher conducted pseudo-static tests to examine the material properties of each under-mat system (no under-mat system, pool noodle under-mat, hockey puck under-mat, and insulation under-mat system) by applying a load and compressing the material to measure its deformation. The measures of the applied force and deformation (displacement) of the material were used to compute the loading and unloading energy, as well as the energy absorption capabilities of each under-mat sample. Each under-mat sample underwent a compression of 12.5 mm for a total of 15 trials at the speed of 25 mm/min or 0.417mm/s to ensure that the testing was considered static. The capacity of the force tester was set to 3000 N to prevent damaging of the Chatillon® force tester. The Chatillon® force tester produced measures of vertical force and displacements. Using the MATLAB® software, force versus displacement plots were created for each loading and unloading cycle of the compressive forces for each condition. Percent measures of compression energy absorption which is also the total energy absorption for each under-mat sample were determined using Equations 5 and 6, respectively. The percent average of energy absorption for each under-mat condition was determined over the second to the 15<sup>th</sup> cycles.

$$\text{Compression Energy Absorption} = \frac{\text{enclosed area of } N \text{ versus compression plot}}{\text{area under loading plot of } N \text{ versus compression}} \quad (5)$$

$$\text{Total Energy Absorption} = \frac{\text{enclosed area of } F_z \text{ versus total displacement plot}}{\text{area under loading plot of } F_z \text{ versus total displacement}} \quad (6)$$

where  $N$  is the compressive force and  $F_z$  is the force in the vertical (or  $Z$ ) direction. And  $N = F_z$ .

### ***Dynamic Testing of the Simulated Head Collision During Free Falling***

The simulated head collision of the tori and uki were conducted using a free-falling vertical impact drop system fitted with an AMTI® force plate at the base of the impactor (see Figure 12). Each under-mat condition (no under-mat, pool noodle, hockey puck, and insulation; see Figure 15) was placed on a wooden block system developed by the researcher and bolted to the force plate (see Figure 16). The wooden block system allowed the under-mat system to be raised to mimic the neck flexion angle at impact due to the difference between the head and trunk falling distance, as outlined by Hashimoto et al. (2015). As such, a difference of 11.83 cm was used. The wooden block system was also fitted with a three plywood side walls (see figure 16) to prevent each under-mat system configuration from sliding between impacts. This feature was necessary, as Judo clubs often build a wooden frame that surrounds both the under-mat system and Judo mat to ensure that its configuration does not separate during practice. The 50<sup>th</sup> percentile height of an average adult Judoka was used to determine the falling distances for the drop tests to conduct the simulations. The drop test under-mat system configurations shown in Figure 15 mimicked the most common under-mat systems used in Judo clubs, which include an under-mat configuration, a wooden frame and a Judo mat.

**Figure 15**

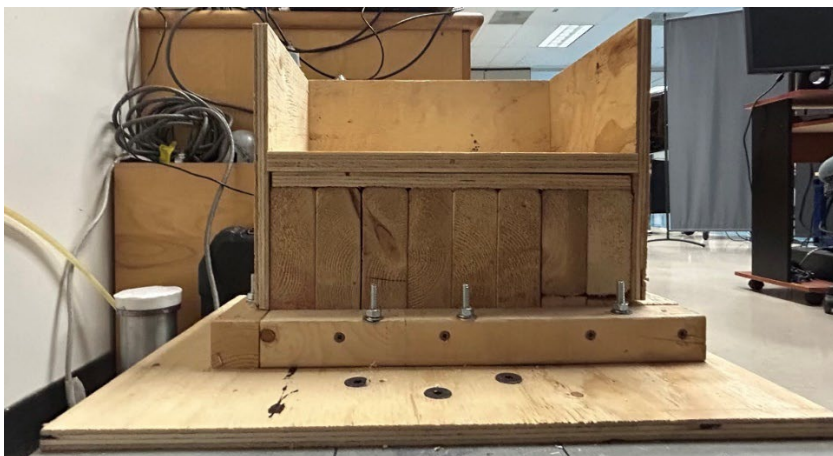
*Under-mat System Conditions (Dynamic Testing)*



*Note.* Under-mat systems from left to right: baseline, pool noodle system, hockey puck system, and insulation system. All were attached to the wooden black system.

**Figure 16**

*Wooden Block System*



An adult NOCSAE® surrogate head form equipped with a hybrid neck was attached to the vertical drop impactor. The head form was dropped from different heights to conduct the simulation tests for Osoto-Gari and Ippon-Seoi-Nage Judo techniques. Before conducting the drop tests, the hybrid neck form was torqued to the 50<sup>th</sup> percentile of the neck strength of an adult Judoka. The exact neck strength value used for this study was 300 N, and it was obtained using the 90-degree cervical neck strength data of adult Judoka reported by Tsuyama et al., (2001). Equation 7 (Pennock et al., 2021) was used to determine the required torque for the neck form.

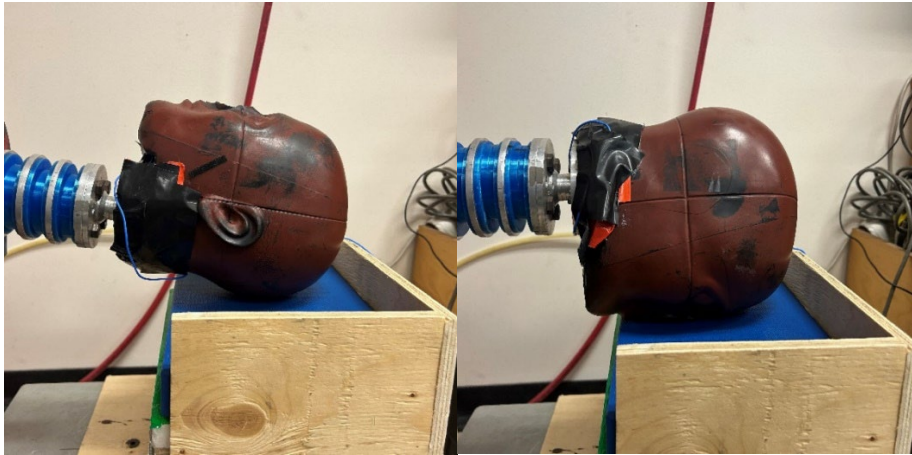
$$t = 0.0213x - 4.2881 \quad (7)$$

where:

$x$  = neck force (N); and

$t$  = torque (Nm).

The calculated neck torque was 2.1 Nm, and the value was used to adjust the mechanical neck form to simulate the 50<sup>th</sup> percentile neck strength level of an adult Judoka. To simulate Osoto-Gari, in which uki's head contacts the mat, the back of the head form was facing the under-mat system placed on top of the force plate. In comparison, to simulate Ippon-Seoi-Nage (see Figure 17), where tori's head would experience the impact, the front of the head was facing the under-mat system placed on top of the force plate. The head and neck forms were attached at a 90-degree angle with respect to the vertical impactor in both cases.

**Figure 17***Impact Drop System Set-up for Throw Simulations*

*Note.* The impactor drop system was set up for Osoto-Gari (left) and Ippon-Seoi-Nage (right).

Each under-mat condition was tested three times for each drop height under each throw-type simulation. The drop heights were set to mimic a throw completed by an athlete no greater than 170.37 cm in height, which was the average Judoka height. However, only half of the average height of a Judoka (85.15 cm) was used to better simulate a real Judo throw with the vertical impactor. To conduct the simulation of the falling heights of the uki, drop heights above the height of the wooden block and under-mat system were increased by 5.68 cm as seen with a digital measuring tool until it reached a max height of 85.15 cm for a total of 15 different drop heights. A total of 360 drops were conducted for a combination of 15 different heights, 2 different throws, 4 mat conditions, and 3 trials per condition, collected at a sampling rate of 20 kHz.

## *Human Participant Testing*

### *Participants*

A first-degree black belt with 20 years of experience was recruited from a local Judo club to participate in the study. This approach was used to minimize variability in throwing styles. The researcher collected the age, body mass, years in Judo, and hand dominance of the participant.

**Inclusion Criteria.** The participant met the inclusion criteria. That is, being at least 24 years old, being able to understand verbal and written instructions, and having the capacity to understand and give informed consent.

**Exclusion Criteria.** The participant had no musculoskeletal injuries in the lower or upper extremities, which might have affected the participant balance and throwing ability. This criterion was important to minimize variability in participant performance.

### *Recruitment*

The participant was recruited through word of mouth, social media advertisements, and posters. The Northwestern Ontario regional director for Judo Ontario was notified of the study to assist with poster distribution. Posters were hung in each Judo club in Thunder Bay (Mountainside Judo Club, Thunder Bay Judo Club, and Kaiju Judo Club). The participant interested in the study was asked to contact the researcher using the information provided in the advertisements and posters. If the previously discussed requirements were met, a date and time was set that worked best for the participant to meet the researcher in the Sanders Building (room SB-1028) for an information meeting and data collection.

### ***Data Collection***

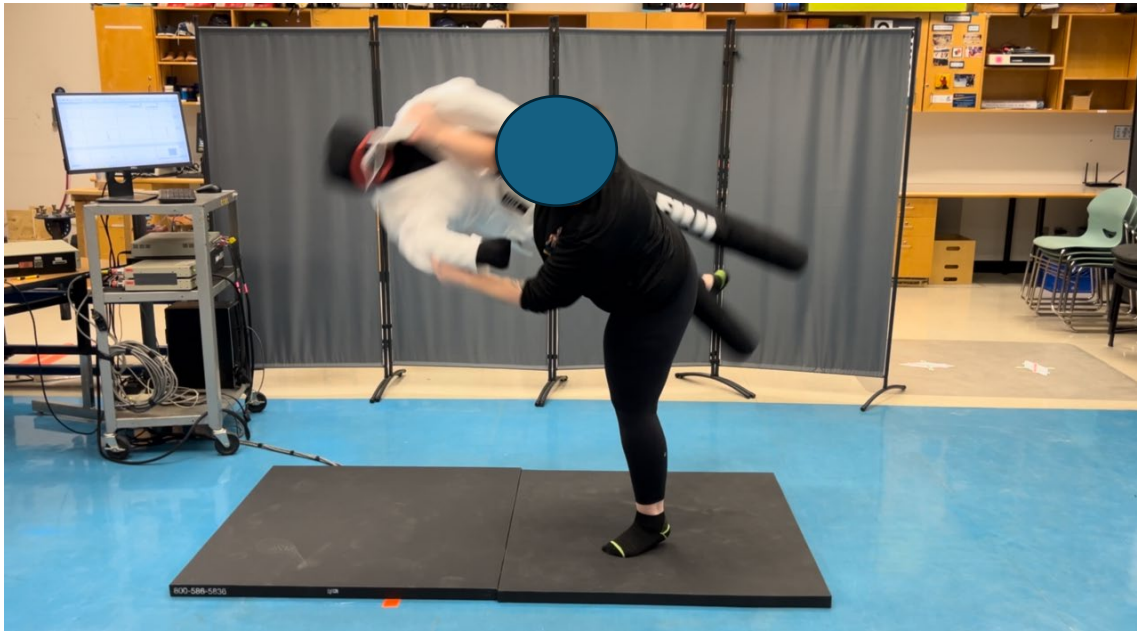
The participant received an information letter to review as well as a letter of consent to sign prior to attending the initial information meeting. Any questions the participant had were answered as they arose. The participant was asked to attend an initial information meeting and data collection session in SB-1028 with the researcher. The participant met the inclusion criteria, chose to participate, and signed a letter of consent. The initial meeting discussed the requirements and purposes of the research. The participant was then assigned a 90-minute time bloc and asked to complete a Get Active Questionnaire (GAQ) and Participant Demographic Questionnaire. The GAQ determined the participant was medically safe to participate in the physical activity associated with the data collection. The participant demographic questionnaire provided information on gender, age, body mass, hand dominance, years in Judo, and belt type. The participant then had the option to complete data collection on the same day or a separate day from the initial meeting.

Before data collection, the AMTI® force plates located in the School of Kinesiology research lab (room SB-1028) were calibrated to the participant's mass by having the participant stand still on one plate for 3 seconds (s). The first AMTI® plate was fitted with a Dax Tatami and used to measure the stability and consistency of the Judoka. This force plate stayed consistent throughout the collection procedure to minimize variability from the participant. The second AMTI® force plate was where the participant completed the tori Judo throws and aimed for the uki Fuji throwing dummy's head to hit the force plate. The under-mat system conditions included no under-mat (considered baseline data), a pool noodle under-mat system, a hockey puck under-mat system, and an insulation under-mat system (see Figure 19). Each under-mat system was placed on the second force plate where the uki (Fuji throwing dummy) hit its head as shown in

Figure 18. This plate also had a mat with a cut-out exposing only the force plate (see Figure 20) to prevent the under-mat systems from sliding during the impact trials. These conditions mimicked a Judo club where the under-mats configurations are placed over a concrete floor.

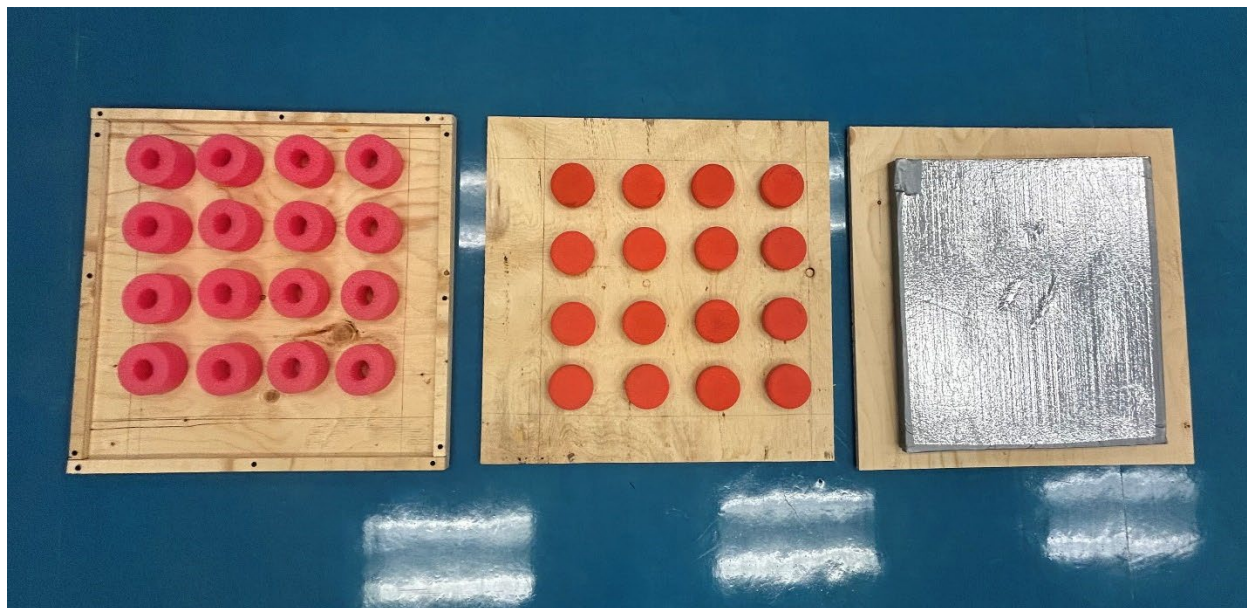
## Figure 18

### *Human Participant Trials Set-up*

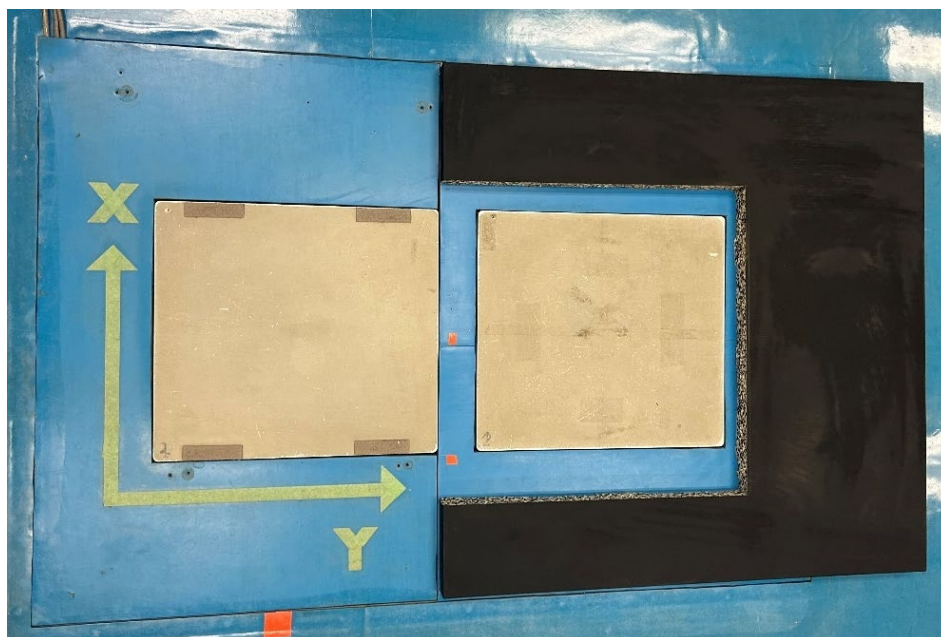


**Figure 19**

*Human Participant Trials Under-mat Conditions*

**Figure 20**

*Under-mat System Frame Set-up (Human Participant Testing)*



The participant began the data collection process by completing 5 min warm up on a stationary bike. Once the warm-up was completed, the participant was given three practice throws for each under-mat condition with the Fuji dummy to get familiar with the dummy weight and throwing procedure. Once the participant was comfortable with the process, the participant was asked to complete 20 Osoto-Gari throws for each condition with their dominant throwing grip (right or left-sided). After each throw, the participant received a 90-second rest period. Between each under-mat condition, the participant received a 5 min rest period. After all trials were completed, a 5 min bike ride at a low intensity was completed as a cool-down for the participant. The independent variable for the human participant testing was the under-mat system used (no under-mat, pool noodle under-mat system, hockey puck under-mat system, and insulation under-mat system). The resultant impact force (N) was the dependent variable.

## **Data Analysis**

### ***Static Material Testing***

The independent variable manipulated for the static material testing was the under-mat system condition (no under-mat, pool noodle, hockey puck, and insulation). The dependent variable measured was energy absorption to compare the different under-mat systems. Descriptive statistics based on means was used to tabulate and compare the percent compressive energy and total energy absorption across the under-mat system conditions.

### ***Simulated Head Collision During Free Falling***

For the dynamic testing with the drop system, the independent variable was the under-mat system condition (no under-mat, pool noodle under-mat system, hockey puck under-mat system, and insulation under-mat system) and throw type (Osoto-Gari and Ippon-Seoi-Nage).

The dependent variables were resultant impact force, linear acceleration, rotational acceleration, HIC, and AGSI values.

A 2-throw type (Osoto-Gari and Ippon-Seoi-Nage)  $\times$  4-under-mat conditions (no under-mat, pool noodle under-mat system, hockey puck under-mat system, and insulation under-mat system) mixed factorial ANOVA with a repeated measure on the second factor was conducted using SPSS® software. The analysis aimed to examine the interaction effect between these two factors on measures of resultant impact force, linear acceleration, rotational acceleration, HIC and AGSI, respectively.

If an interaction effect was found, a simple main effect analysis technique was conducted to help explain the interaction for each dependent variable, respectively. If no interaction occurred, the main effect for each factor was examined using one-way ANOVAs for repeated measures and t-tests for independent measures. The Bonferroni statistical technique was used for pair mean comparisons.

### ***Human Participant Testing***

The independent variable for the human participant testing was the under-mat system used (no under-mat, pool noodle, hockey puck, and insulation). The dependent variable was the resultant impact force (N). The participant demographic was tabulated. Descriptive statistics, including the mean and standard deviations was used to compare the under-mat conditions for the measures of force based on the Osoto-Gari Judo throw.

## Chapter 4 - Results

The results of this study addressed each research question individually. The static testing analysis included measures of compressive energy absorption. The dynamic testing analysis included measures of linear and angular accelerations to determine the risk of head injury, which was quantified using HIC and AGSI index values. The human participant testing analysis included measures of impact force.

### Static Testing

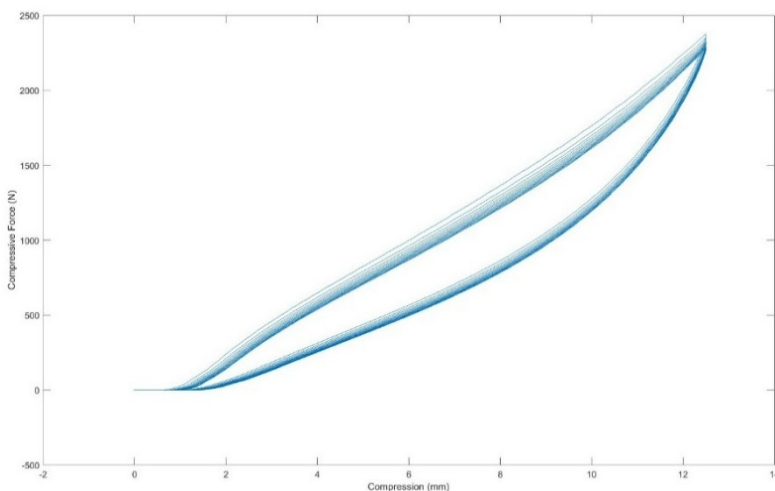
**Research Question One.** The researcher hypothesized that the baseline under-mat condition would absorb the most energy when compared to the other under-mat conditions during static testing. In relation to this hypothesis, force–displacement plots were generated for each loading and unloading cycle for all the under-mat test conditions (baseline, pool noodle, hockey pucks, and insulation) as shown in Figures 21–24. The area enclosed between the loading and unloading curves for each test condition represents the energy absorbed by each under-mat material. When examining the compressive force over 12.5 mm of displacement as an indicator of loading energy, the baseline under-mat system exhibited the highest compressive force (see Figure 21), while the pool noodle condition demonstrated the lowest (see Figure 22), relative to the hockey puck and insulation systems.

Across all conditions, the unloading forces were consistently lower than the corresponding loading forces, indicating viscoelastic behaviour, typical of energy-dissipating materials (Ashby et al., 2012; Davidson et al., 2009). Among the materials tested, the pool noodle displayed the greatest compliance, characterized by a lower loading slope and lower stiffness compared with the other under-mat systems. To further explain the material property behaviour of the under-mat systems, the energy absorption was quantified by calculating the total

compressive energy absorbed for each condition. The results indicated that the baseline under-mat absorbed the largest amount of compressive energy ( $M=3.74$  J), followed by the insulation ( $M=2.28$  J) and hockey puck ( $M=1.58$  J) conditions. In contrast, the pool noodle exhibited the lowest energy absorption ( $M=0.32$  J). These mean differences in compressive energy absorption across under-mat systems are presented in Figure 25. This outcome suggests that the baseline under-mat system stores more energy and releases less during rebound, consistent with viscoelastic energy loss. In the context of Judo under-mats, higher energy dissipation is desirable as it reduces rebound; however, excessive stiffness can increase transmitted forces, potentially diminishing impact attenuation performance.

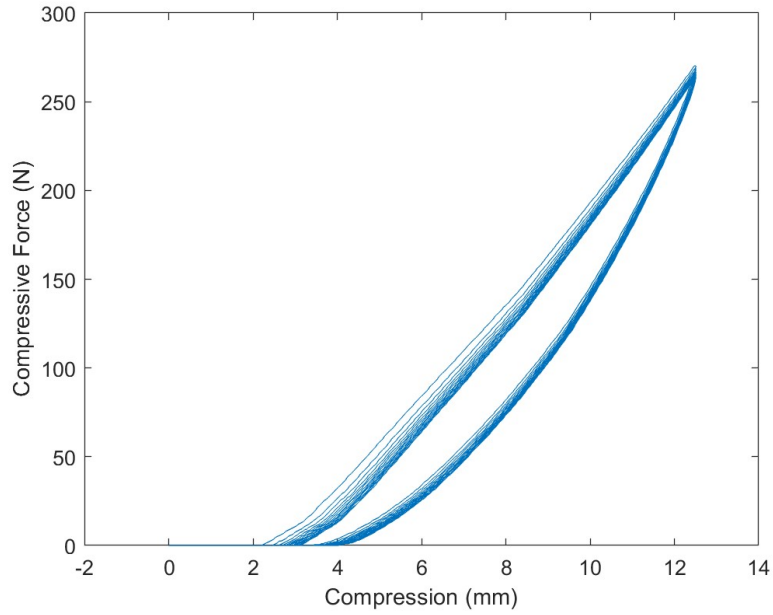
### Figure 21

#### *Baseline Compressive Force Versus Total Compressive Displacement*

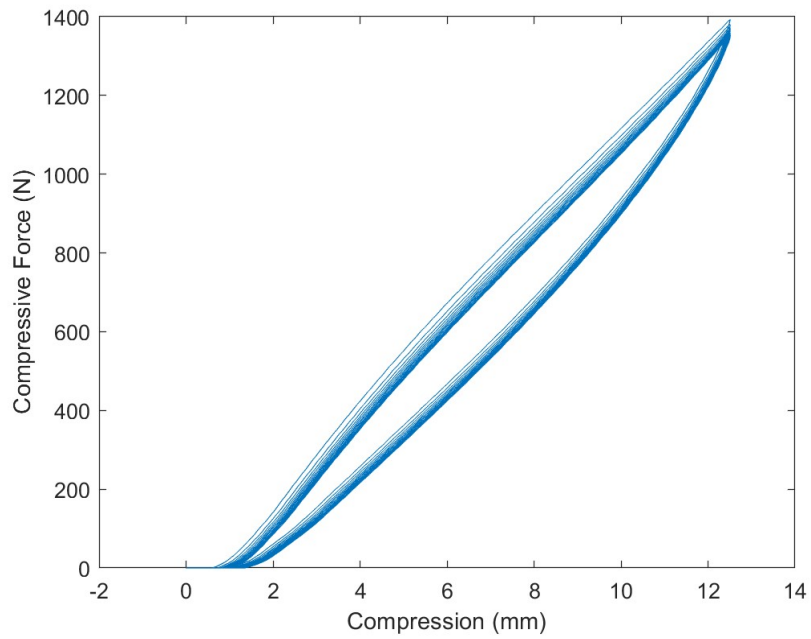


**Figure 22**

*Pool Noodle Compressive Force Versus Total Compressive Displacement*

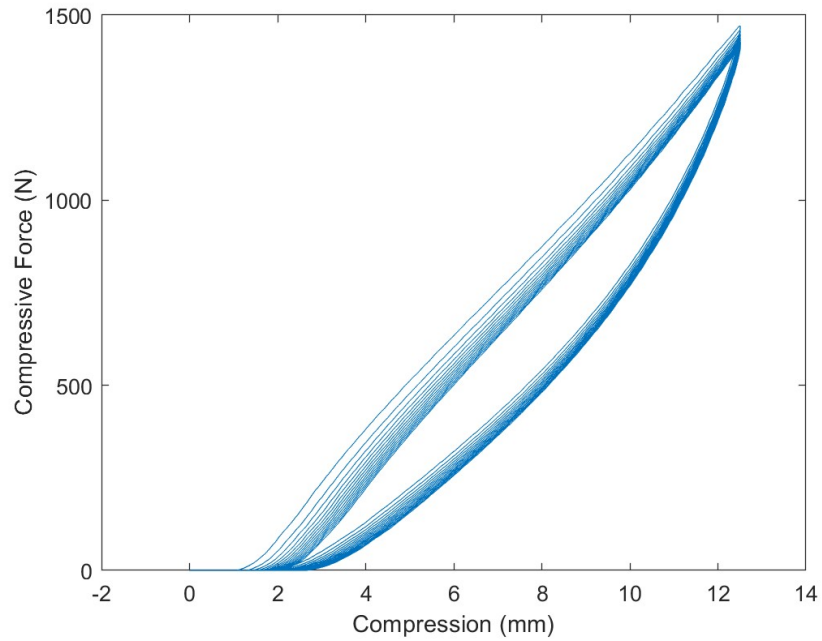
**Figure 23**

*Hockey Puck Force Versus Total Compressive Displacement*

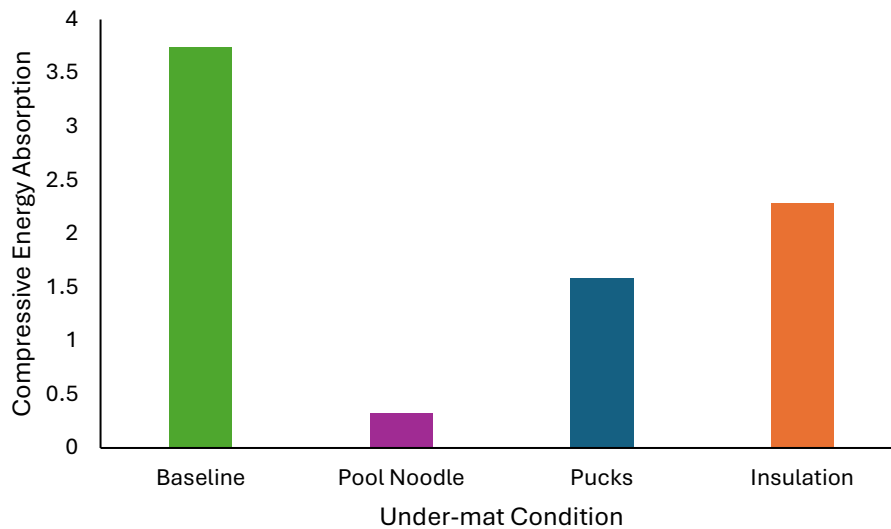


**Figure 24**

*Insulation Compressive Force Versus Total Compressive Displacement*

**Figure 25**

*Mean Compressive Energy Absorption for Each Under-mat Condition*



The percentage of energy absorption was also quantified by using Equations 5 and 6 to calculate the ratio of energy absorbed per joule of loading energy for each condition. The results suggest that the insulation under-mat absorbed the largest amount of energy per joule of loading energy (M=30.7%), followed by the baseline (M=30.4%) and pool noodle system (M=28.3%) conditions. In contrast, the hockey pucks exhibited the lowest percentage of energy absorbed per joule of loading energy (M=19.8%). These mean differences in energy absorption across under-mat systems are presented in Table 1.

**Table 1**

*Static Testing Summary Results*

Under-mat Condition	Loading Energy (J)	Unloading Energy (J)	Absorbed Energy (J)	Ratio
Baseline	12.312	-8.565	3.746	0.304
Pool Noodle	1.161	-0.832	0.329	0.283
Hockey Pucks	7.961	-6.377	1.583	0.198
Insulation	7.427	-5.138	2.289	0.307

**Dynamic Testing**

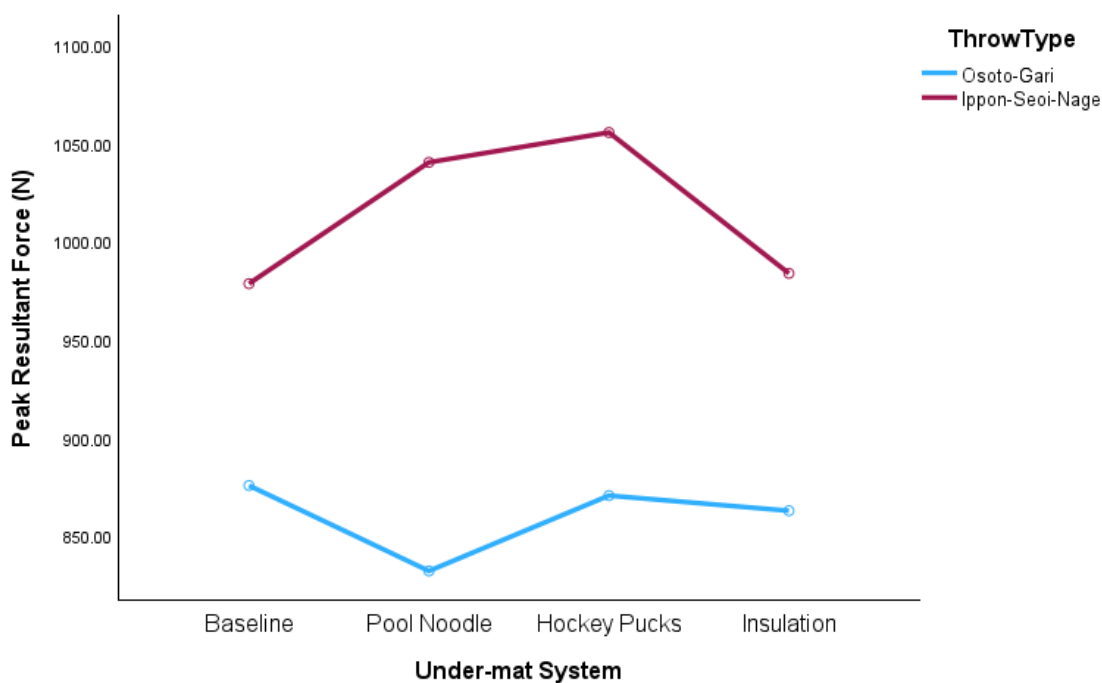
**Research Question Two.** The researcher hypothesized that the pool noodle under-mat condition would absorb the most force, minimize the most linear and rotational impact accelerations when compared to the other under-mat conditions for both simulated Judo throwing techniques. The researcher addressed this question by conducting 2 (throw type: Osoto-Gari and Ippon-Seoi-Nage)  $\times$  4 (under-mat systems: baseline, pool noodle, hockey pucks, and insulation) mixed factorial ANOVAs with a repeated measures on the second factor to examine the interaction

effect between these two factors on measures of force absorption, linear acceleration, and rotational acceleration, respectively.

**With respect to resultant force.** Prior to conducting the two-way mixed factorial ANOVA, the assumption of sphericity regarding equal variance across under-mat conditions for the measure of resultant force was evaluated. Mauchly's Test of Sphericity indicated that this assumption was violated,  $\chi^2(5)=36.32, p<.05$ . Therefore, the Greenhouse Geisser correction was applied to the degrees of freedom ( $\epsilon=1.69$ ). The mixed factorial ANOVA indicated a significant interaction effect between throw type and under-mat condition,  $F(1.69, 47.46) = 5.906, p<.05, \eta^2=0.174$  (large effect) on measures of resultant force as shown in Figure 26.

**Figure 26**

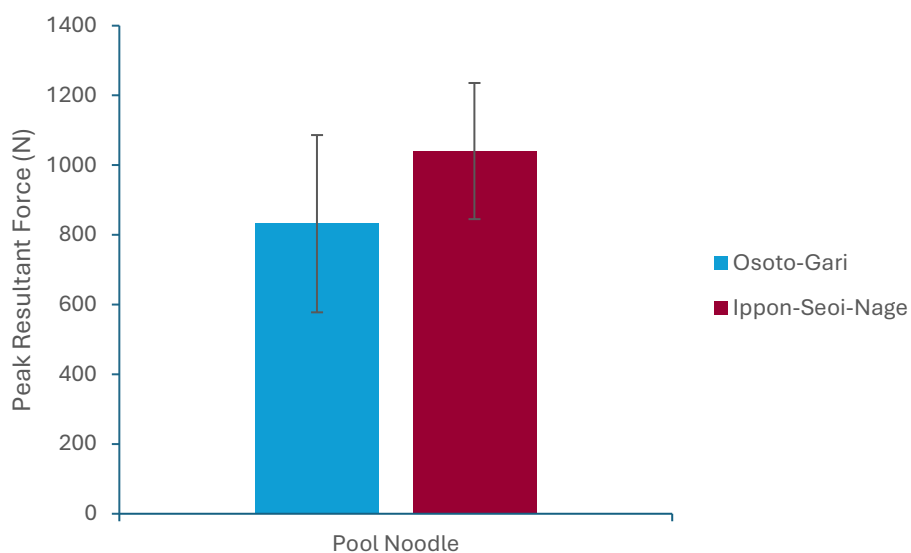
*Peak Resultant Force Interaction Effect*



To help explain this interaction effect, the researcher conducted a simple main effect analysis to examine the effect of throw type at each under-mat condition, respectively, on measures of resultant force. Bonferroni pair mean comparison indicated significant differences between Osoto-Gari and Ippon-Seoi-Nage throw type for the pool noodle condition ( $M_{(diff)} = -208.36\text{N}$ ,  $SE=80.93$ ,  $95\% \text{ CI}:[42.56,374.14]$ ,  $p<.05$ ) and the hockey puck condition ( $M_{(diff)} = -185.13\text{N}$ ,  $SE=76.85$ ,  $95\% \text{ CI}:[-343.55,-27.70]$ ,  $p<.05$ ) as shown in Figures 27 and 28.

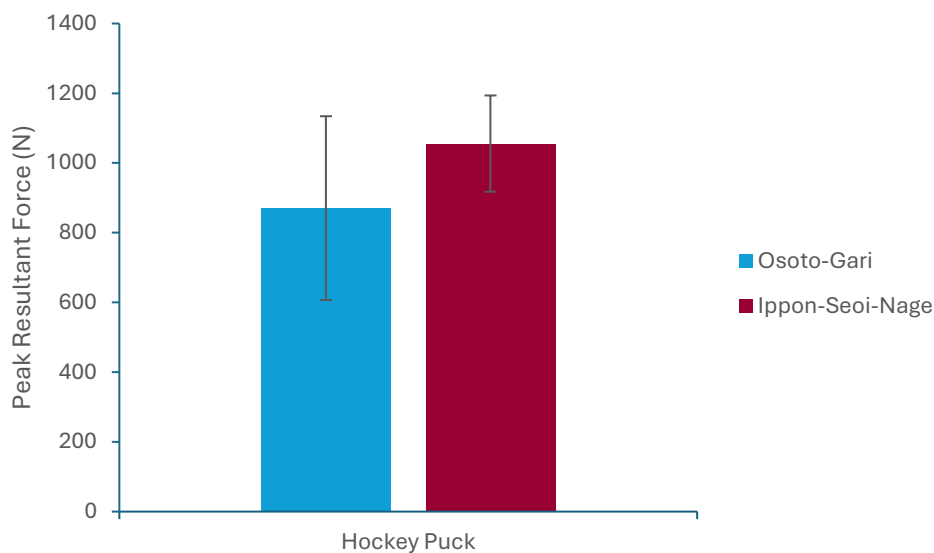
### Figure 27

*Simple Main Effect Pool Noodle on Resultant Force*



**Figure 28**

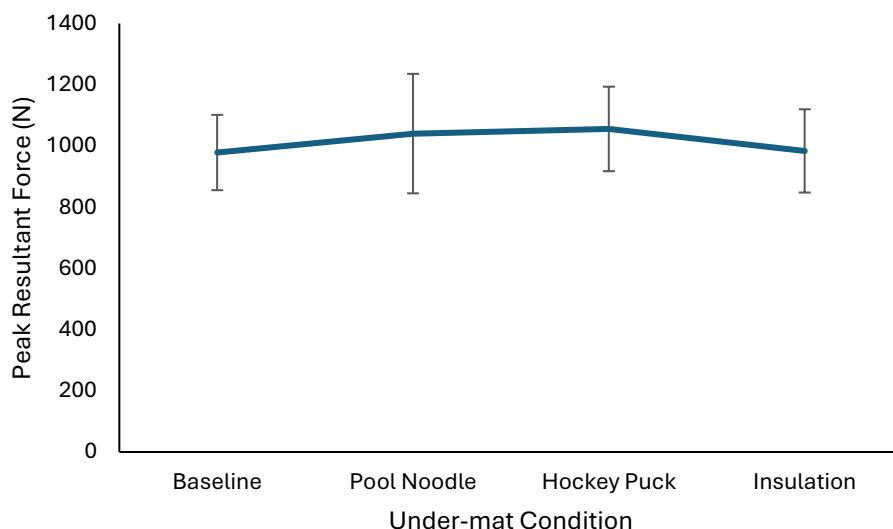
*Simple Main Effect Hockey Puck on Resultant Force*



The researcher also conducted one-way repeated measures ANOVAs to examine the simple main effect of under-mat condition at each throwing type separately for measures of resultant force to further explain the interaction effect. The results only revealed significant differences across under-mat condition for the Ippon-Seoi-Nage Judo throw on measures of force absorption,  $F(3, 26)=20.26, p<.05, \eta^2=0.704$  (large effect). A Bonferroni post hoc analysis indicated that the differences between under-mat condition for the Ippon-Seoi-Nage Judo throw on measures of resultant force were between baseline and hockey puck ( $M_{(diff)}=-77.07$  N,  $SE=25.04, 95\% CI: [-148.17, -5.97], p<.05$ ); pool noodles and insulation ( $M_{(diff)}=-56.62$  N,  $SE=13.61, 95\% CI: [17.97, 95.27], p<.05$ ) as shown in Figure 29.

**Figure 29**

*Simple Main Effect Under-mat Resultant Force for Ippon-Seoi-Nage*



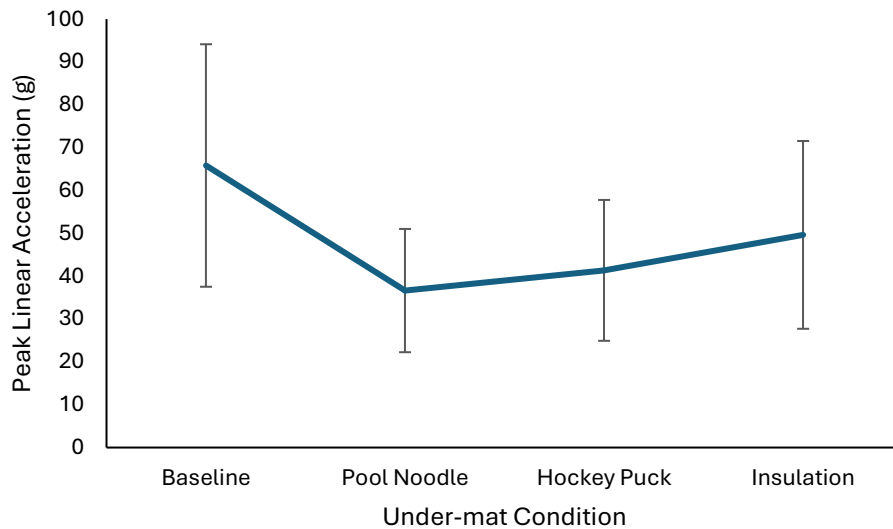
***With respect to linear acceleration.*** The assumption of sphericity for measures of linear acceleration was examined across under-mat conditions. Mauchly's Test of Sphericity indicated that this assumption was violated,  $\chi^2(5)=36.32, p<.05$ . Therefore, the Greenhouse Geisser correction was applied to the degrees of freedom ( $\epsilon=1.12$ ). The mixed factorial ANOVA indicated no significant interaction effect between throw type and under-mat condition,  $F(1.12, 31.40)=3.12, p>.05, \eta^2=0.10$  (*medium effect*) on measures of linear acceleration. Since there was no interaction effect, the main effects of throw type and under-mat conditions were examined separately.

When examining the main effect of throwing type, the results indicated no significant differences between Osoto-Gari and Ippon-Seoi-Nage on measures of linear acceleration,  $F(1,28)=1.50, p>.05, \eta^2=.86$ . The result, however, indicated a significant main effect of under-mat condition on measures of linear acceleration,  $F(1.12, 31.40)=90.01, p<.001, \eta^2=0.76$  (*large effect*) as shown in Figure 30. Bonferroni pair mean comparison indicated that the differences in

measures of linear acceleration were between baseline and pool noodles ( $M_{(diff)}=29.05$  g,  $SE=3.02$ , 95% CI:[22.87, 35.23],  $p<.05$ ); baseline and hockey puck ( $M_{(diff)}=24.47$  g,  $SE=2.32$ , 95% CI:[19.90, 29.05],  $p<.05$ ); baseline and insulation ( $M_{(diff)}=16.19$  g,  $SE=1.20$ , 95% CI:[13.63, 18.75],  $p<.05$ ); pool noodle and hockey puck ( $M_{(diff)}=-4.56$  g,  $SE=.96$ , 95% CI:[-6.55, -2.59],  $p<.05$ ); pool noodle and insulation ( $M_{(diff)}=-12.86$  g,  $SE=1.94$ , 95% CI:[-16.85, -8.87],  $p<.05$ ) and hockey puck and insulation ( $M_{(diff)}=-8.28$  g,  $SE=1.18$ , 95% CI:[-10.70, -5.86],  $p<.05$ ).

### Figure 30

*Main Effect Under-mat System on Peak Linear Acceleration (g)*



***With respect to angular acceleration.*** The assumption of sphericity for measures of angular acceleration was examined across under-mat conditions. Mauchly's Test of Sphericity indicated that this assumption was violated,  $\chi^2(5)=14.22$ ,  $p<.05$ . Therefore, the Greenhouse Geisser correction was applied to the degrees of freedom ( $\epsilon=2.23$ ). The mixed factorial ANOVA indicated no significant interaction effect between throw type and under-mat condition,  $F(2.23, 62.41)=1.17$ ,  $p>.05$ ,  $\eta^2=0.04$  (small effect) on measures of angular acceleration. Since there was

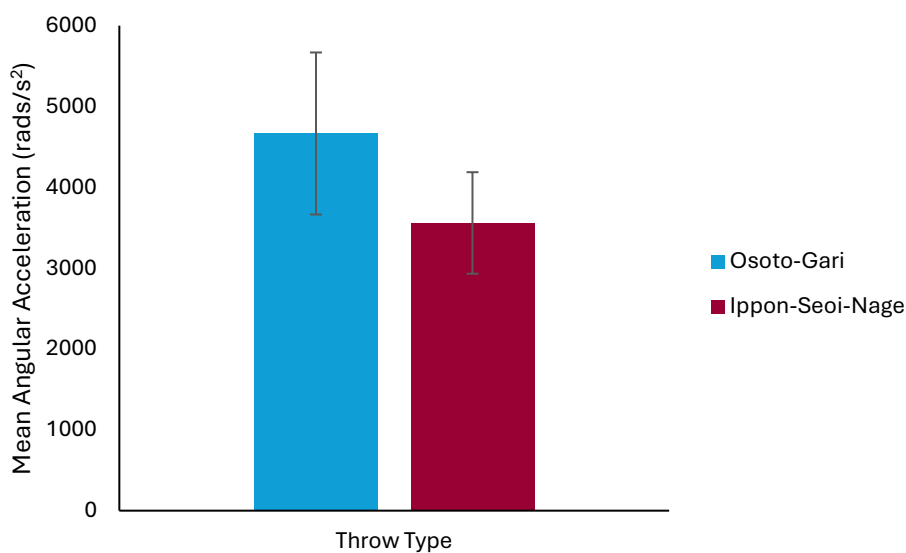
no interaction effect, the main effects of throw type and under-mat conditions were examined separately.

When examining the main effect of throwing type, the results indicated significant differences between Osoto-Gari ( $M=4665.97$ ,  $SD=1002.19$ ) and Ippon-Seoi-Nage ( $M=3558.91$ ,  $SD=628.21$ ) on measures of angular acceleration,  $F(1,28)=13.14$ ,  $p<.05$ ,  $\eta^2=0.319$  (*large effect*) as shown in Figure 31. The results also indicated a significant main effect of under-mat condition on measures of angular acceleration,  $F(2.23, 62.41)=3.08$ ,  $p<.05$  as shown in Figure 32.

Bonferroni pair mean comparison indicated that the differences in measures of angular acceleration were significant between baseline and pool noodles ( $M_{(diff)}=1411.70$   $\text{rads/s}^2$ ,  $SE=541.77$ , 95% CI:[301.931, 2521.473],  $p<.05$ ); pool noodles and insulation ( $M_{(diff)}=-1305.96$   $\text{rads/s}^2$ ,  $SE=554.87$ , 95% CI:[-2442.58, -169.35],  $p<.05$ ), and hockey pucks and insulation ( $M_{(diff)}=-1034.27$   $\text{rads/s}^2$ ,  $SE=494.49$ , 95% CI:[-2047.20, -21.34],  $p<.05$ ).

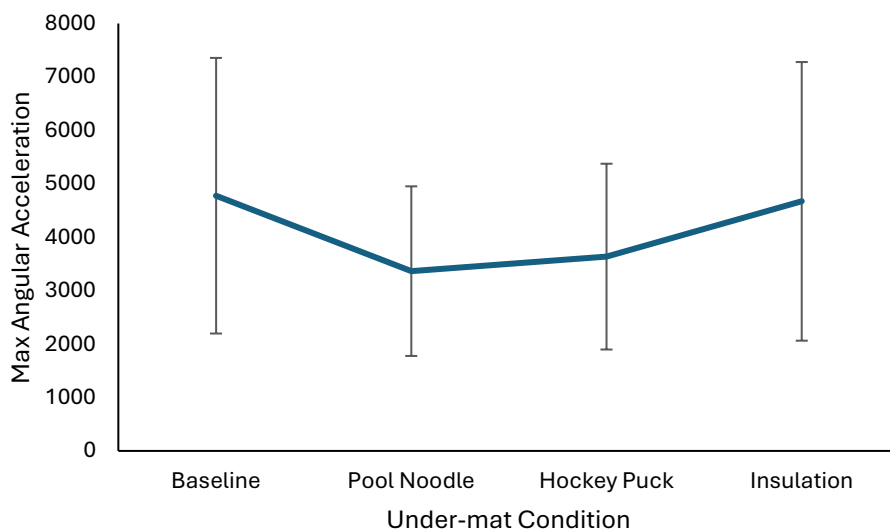
### Figure 31

*Main Effect of Throw Type on Mean Angular Acceleration (rads/s<sup>2</sup>)*



**Figure 32**

*Main Effect Under-mat System on Max Angular Acceleration*



**Research Question Three.** The researcher hypothesized that the pool noodle under-mat condition would have the lowest risk of head injury as measured by HIC and AGSI, respectively, when compared to the other under-mat conditions for both simulated Judo throwing techniques.

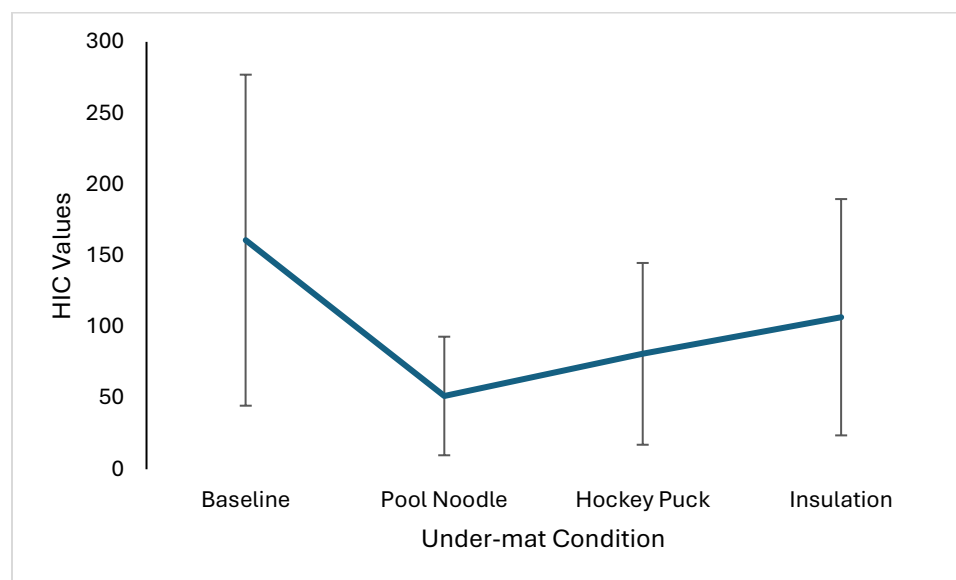
**With respect to HIC.** The assumption of sphericity for measures of HIC was examined across under-mat conditions. Mauchly's Test of Sphericity indicated that this assumption was violated,  $\chi^2(5)=122.64, p<.001$ . Therefore, the Greenhouse Geisser correction was applied to the degrees of freedom ( $\epsilon=1.09$ ). The mixed factorial ANOVA indicated no significant interaction effect between throw type and under-mat condition,  $F(1.09, 30.5)=1.070, p>.05, \eta^2=0.04$  (*medium effect*) on measures of HIC. Since there was no interaction effect, the main effects of throw type and under-mat conditions were examined separately.

When examining the main effect of throw type, the results also indicated no significant differences between Osoto-Gari and Ippon-Seoi-Nage on measures of HIC,  $F(1,28) = 1.43, p>.05, \eta^2=.04$  (*medium effect*). The result, however, indicated a significant main effect of under-

mat condition on measures of HIC,  $F(1.09, 30.5)=55.13, p < .001, \eta^2=0.66$  (large effect) as shown in Figure 33. Bonferroni pair mean comparison indicated that the significant difference in measures of HIC were between baseline and pool noodles ( $M_{(diff)}=109.36, SE=14.28, 95\% CI:[80.09, 138.62], p<.001$ ); baseline and hockey pucks ( $M_{(diff)}=79.78, SE=10.45, 95\% CI:[41.43, 101.20], p<.001$ ); baseline and insulation ( $M_{(diff)}=54.07, SE=6.17, 95\% CI:[41.43, 66.71], p<.001$ ). Significant differences on measures of HIC were also seen between the pool noodle and hockey pucks ( $M_{(diff)}=-29.57, SE=4.67, 95\% CI:[-39.15, -20.00], p<.001$ ); pool noodle and insulation ( $M_{(diff)}=-55.28, SE=8.46, 95\% CI:[-72.60, -37.96], p<.001$ ); and finally the hockey pucks and insulation ( $M_{(diff)}=-25.70, SE=4.89, 95\% CI:[-35.73, -15.68], p<.001$ ).

### Figure 33

*Main Effect Under-mat System on HIC*



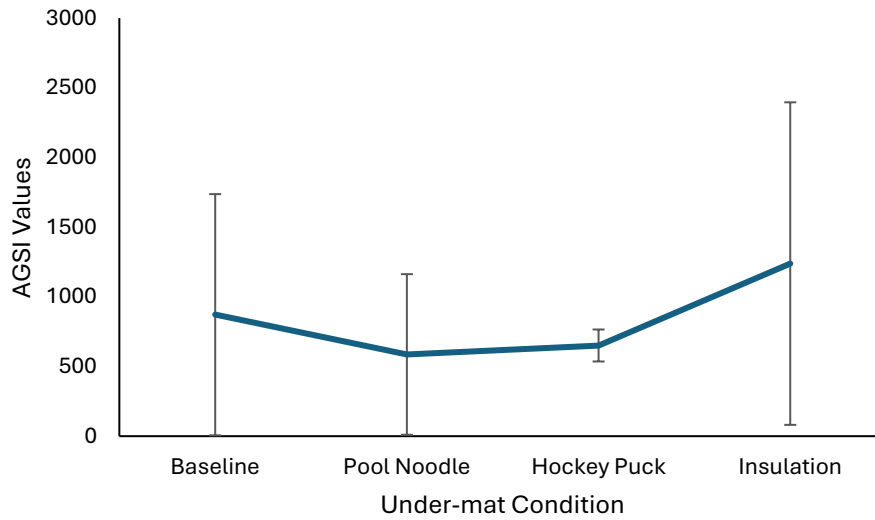
***With respect to AGSI.*** The assumption of sphericity for measures of AGSI was examined across under-mat conditions. Mauchly's Test of Sphericity indicated that this assumption was violated,  $\chi^2(5)=12.01, p<.05$ . Therefore, the Greenhouse Geisser correction was applied to the

degrees of freedom ( $\varepsilon=2.28$ ) and the mixed factorial ANOVA indicated no significant interaction between throw type and under-mat condition,  $F(2.28, 63.96)=2.433, p>.05, \eta^2=0.09$  (*large effect*) on measures of AGSI. Since there was no interaction effect, the main effects of throw type and under-mat conditions were examined separately.

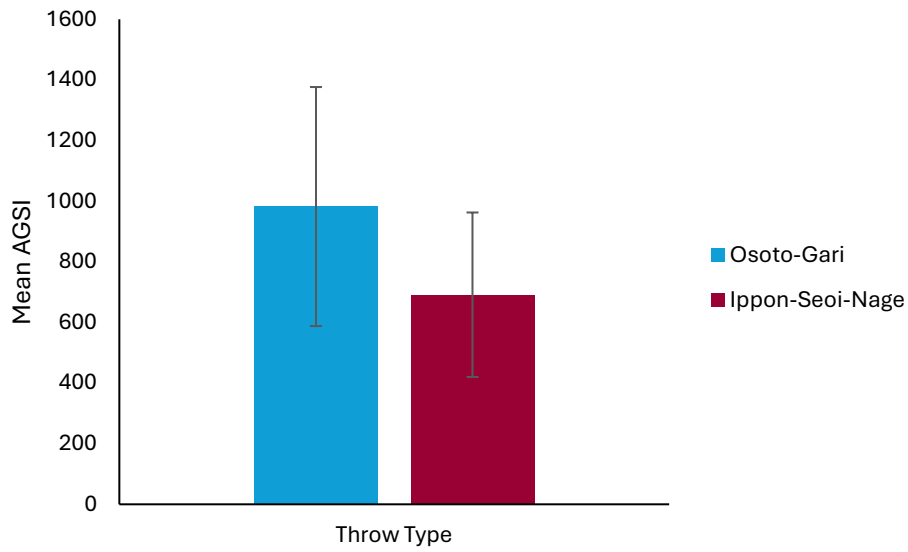
The result, however, indicated a significant main effect of under-mat condition on measures of AGSI,  $F(2.28, 63.96)=3.53, p<.05, \eta^2=0.11$  (*large effect*) as shown in Figure 34. Bonferroni pair mean comparison indicated that the significant difference in measures of AGSI were between the pool noodles and insulation ( $M_{(diff)}=652.07, SE=221.97, 95\% CI:[197.38, 1106.75], p<.05$ ) and the hockey pucks and insulation systems ( $M_{(diff)}=587.59, SE=228.72, 95\% CI:[119.06, 1056.12], p<.05$ ). When examining the main effect of throw type, the results indicated significant differences between Osoto-Gari (Mean=982.29, SD=394.23) and Ippon-Seoi-Nage (M= 691.42, SD=271.29) on measures of AGSI,  $F(1,28)=5.541, p<.05, \eta^2=0.165$  (*large effect*) as shown in Figure 35.

**Figure 34**

*Main Effect of Under-mat System on AGSI*

**Figure 35**

*Main Effect of Throw Type on AGSI*



## Human Participant Testing

**Research Question Four.** The researcher hypothesized that the pool noodle under-mat condition would absorb the most force as compared to the other under-mat conditions when the uki simulated dummy was thrown by a human with advanced-level Judoka.

The participant demographic questionnaire indicated that the participant was a black belt with 20 years of Judo experience, as seen in Table 2. The participant was a female who was right hand dominant and as such completed the throwing conditions with a right-handed grip.

**Table 2**

Participant Demographic Questionnaire

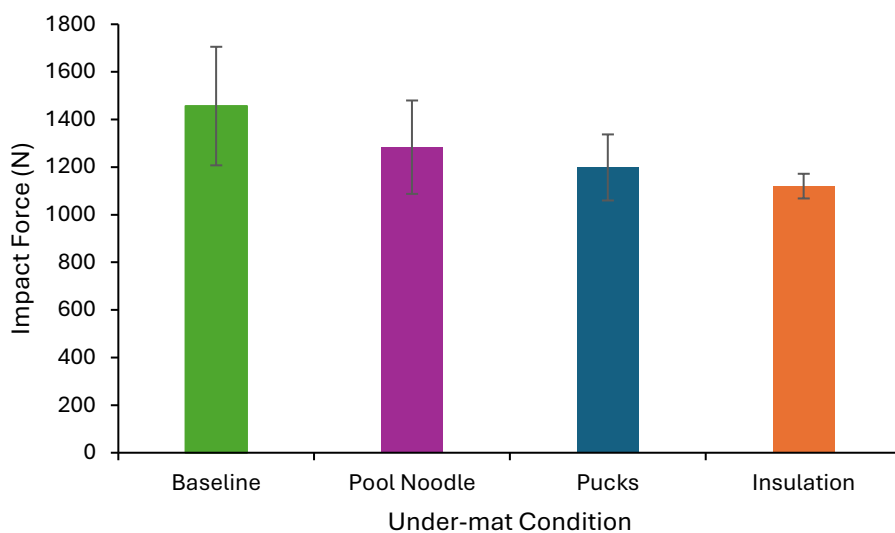
Participant Demographics	
Age	24
Sex	Female
Height (cm)	167.64
Body Mass (kg)	102.8
Dominant Grip	Right
Belt Colour	Black
Years in Judo	20
Inclusion Criteria	
Do you have a history of lower of upper extremity trauma in the past year?	No
Do you have a history of arthritis?	No
Do you have any foot/knee/hip/spine pain impacting balance or throwing ability?	No
Do you have any neurological conditions impacting balance or throwing ability?	No

Descriptive statistics were used to examine the differences between under-mat conditions, when the dummy was thrown by the experienced Judoka. The baseline condition produced the highest mean impact force, as shown in Figure 36 and Table 3. All under-mat systems reduced the mean impact force relative to the baseline, with reductions of approximately 12% for the pool

noodle, 18% for the hockey pucks, and 23% for the insulation layer. The insulation system not only achieved the highest reduction in impact force but also demonstrated the lowest variability, suggesting more consistent impact attenuation. However, despite its effectiveness, the insulation material may deteriorate over time due to its limited ability to return to its original shape after repeated impacts, potentially compromising long-term performance. Considering both performance and material resilience, the hockey puck system, followed by the pool noodle system as depicted in Figure 36 and Table 3, may represent more practical and durable options for under-mat applications.

**Figure 36**

Mean Impact Force for Each Under-mat Condition



**Table 3**

*Descriptive Statistics of Mean Impact Force for Each Condition*

	Mean (N)	Standard Deviation
Baseline	1456.38	249.01
Pool Noodle	1283.64	196.18
Hockey Pucks	1198.53	138.74
Insulation	1120.07	51.82

## Chapter 5 - Discussion

Despite the growing awareness of concussion and TBI risk in sports, comprehensive research into the efficacy of Judo mat systems in mitigating impact forces remains limited (Raymond et al., 2021). Given that the material properties of Judo under-mat systems can affect energy absorption and dissipation during impacts, it is crucial to investigate the extent to which these materials play a role in reducing head injury risk. Without regulations controlling the implementation of under-mat systems, many Judo clubs may inadvertently expose Judoka to suboptimal under-mat systems by creating low-cost alternatives as an avenue to mitigate head injuries and concussion risk. Based on this concern, the materials commonly used for under-mat systems in Canada have yet to be explored in relation to their capabilities to diminish head injury risk.

The present study sought to address this gap by evaluating the effectiveness of various under-mat materials in reducing impact force, linear acceleration, angular acceleration, and risk of head injury (AGSI and HIC) associated with typical Judo throws and use the empirical data to inform safer under-mat system designs (Carlson et al., 2016; Ta et al., 2024). The researcher selected the pool noodle under-mat system due to its widespread use and relatively low cost to build in Judo clubs. The under-mat insulation system was selected due to its prevalence in some Judo clubs, offering another accessible and potentially cost-effective alternative. The hockey puck under-mat system, although the most expensive setup, was selected because it is implemented in some Judo clubs in Ontario. This research evaluated the performance of the under-mat systems under controlled fall simulations for two prevalent Judo throws including Ippon-Seoi-Nage and Osoto-Gari. The results of this study are discussed based on the static compression, dynamic impact, and human participant tests conducted on the selected under-mat

systems, as well as the potential implications for injury prevention in Judo, particularly concerning head impacts and concussions.

### **Static Material Testing**

The focus of static testing in the current study was to examine how the under-mat system materials deform and absorb energy under uniaxial compressive stress. This approach is particularly relevant for materials designed for energy absorption to assess their performance (Ashby & Jones, 2012). The evaluation of compression energy under static conditions has been widely used to assess foams and cellular structures of materials to manage impact or repetitive loading (Ashby & Jones, 2012). In the current study, the force-displacement characteristics obtained from the static tests allowed the researcher to conduct a direct comparison of energy absorption properties of the under-mat system configurations. This comparative approach is useful to gather information about the capabilities of the materials to deform under compression and absorb a percentage of the loaded energy (Davidson et al., 2009).

The findings of the current study align with the conceptual framework of static testing stated by Ashby et al. (2012) and Davidson et al. (2009). The results suggested that when a static load was applied to the under-mat systems, the baseline condition represented by the Judo mat demonstrated the highest compressive energy absorption as shown in Figure 25 and Table 1. Although the Judo mat deformed the same amount of displacement as the other under-mat systems tested under identical loading conditions, it absorbed the highest amount of energy because it required a very high force to deform, which translated into a high level of stiffness as compared to the other under-mat systems. This outcome suggests that the Judo mat can potentially reduce high-impact forces during dynamic collisions, but with less cushioning, resulting in more force being induced on the human during a fall.

While higher levels of stiffness can lead to more energy being transferred to the human during a fall, a certain level of stiffness is required to prevent the material from bottoming out and reaching complete saturation (Xiao et al., 2022). The ideal material for impact mitigation often has a specific force-displacement curve to manage energy across different impact intensities (Xiao et al., 2022). A material with a highest compressive energy absorption in static testing may not provide the appropriate safety for the athlete if it requires a high force to deform, particularly in dynamic head collisions concerning head trauma, as excessive stiffness can lead to higher impact forces being induced to the human head despite greater energy absorption, a critical concept used in helmet design (Luo & Liang, 2017; Ta et al., 2024).

In the case of stiffness, it is also important to consider the dynamic energy absorption efficiency of the material, which often differs significantly from static measurements (Xiao et al., 2022). Material stiffness can vary depending on the strain rate and the impact area (Crolan et al., 2022; Luo & Liang, 2017). This implies that while a material may exhibit high energy absorption under static loads, its performance under dynamic impact conditions, such as those experienced during a Judo fall, could differ substantially, thereby, affecting its effectiveness in injury prevention (Caccese et al., 2014). For example, a lack of cushioning can translate into more energy being introduced to the head of the athlete due to the delayed response of the material to deform and absorb the impact energy (Caccese et al., 2014).

Conversely, materials exhibiting lower stiffness under the same amount of deformation, such as the hockey pucks, pool noodles, and the insulation, absorbed less energy. This outcome translates into more cushioning for the athlete to possibly reduce impact forces transmitted to the head. Thus, under-mat systems with more viscoelastic behaviour may provide more protection to the head during dynamic collisions since these materials can deform more easily. Nonetheless,

caution is necessary, as a greater risk of injury is possible if the impact force exceeds the stiffness threshold levels of the material to absorb energy during a dynamic impact (Drane et al., 2020).

When looking at the percentage of compressive or total energy absorption of the material, it seemed that the insulation under-mat system was slightly better than the baseline condition, with a mean percentage energy absorption of 30.77% and 30.41%, respectively. The pool noodles had a mean energy absorption of 28.30%, which was lower than the baseline and insulation. This outcome indicated that the pool noodles required the least amount of force to deform, translating into more comfort to the athlete due to its low stiffness. The hockey puck system, however, demonstrated the lowest percentage of energy absorption with 19.88%, indicating a reduced capacity for dissipating impact energy under static loading conditions, but lower stiffness compared to the baseline and insulation (Berry et al., 2022). This outcome suggests that while the hockey puck and pool noodles systems may translate into more comfort, and the systems might offer structural support, caution may be taken when the impact forces exceed the compliance range of the material, which is crucial for head injury prevention in sports (Ramirez & Gupta, 2019).

In summary, the results from the static analysis are critical for understanding the potential of the under-mat systems in mitigating impact forces before conducting dynamic activities (Zhang et al., 2008). This approach is particularly pertinent in sports like Judo to select more effective energy absorption material for under-mat systems to mitigate injury risk and more specifically, concussion risk (Caccese et al., 2016; Hajiaghamemar et al., 2015).

## Dynamic Testing

Dynamic testing plays a critical role in evaluating the performance of the material, particularly under-mat systems, which are designed to mitigate head injury risk in the sport of Judo (Kazl & Torres, 2019; Wicklund et al., 2021). Unlike static testing, which characterizes a material's behaviour under slow loading, dynamic testing replicates real-world impact conditions to simulate falls or collisions (Post et al., 2017). These tests allow for quantification of impact force attenuation, linear and rotational accelerations, as well as risk of head injury directly linked to the potential for concussion (Post et al., 2017). Linear acceleration has historically been the primary metric used to assess head injury risk, as it relates to translational motion of the head and the resulting intracranial pressure gradients (Newman et al., 2005). However, subsequent studies have emphasized the critical contribution of rotational acceleration to diffuse brain injuries, including concussions and subdural hematomas, as angular motion induces shear strains within the neural tissue (Gennarelli et al., 1987; King et al., 2003). Similar to the work completed by Pennock et al. (2021), the dynamic impact testing conducted in this study used a vertical drop impactor to quantify impact forces and accelerations across different under-mat configurations to estimate head injury risk as measured by HIC and AGSI (Murayama et al., 2013).

***Impact Force.*** The present study found that across 360 vertical drops, a significant interaction effect between throw type and under-mat condition was observed on measures of resultant force. This outcome suggests that the effectiveness of the under-mat systems in mitigating impact force differs between Osoto-Gari and Ippon-Seoi-Nage Judo throwing techniques. Specifically, significant differences in resultant force were observed when using the pool noodle and hockey puck under-mat systems. The inclusion of these specific under-mat systems appears to lessen the impact force more effectively for head impacts occurring at the

back during an Osoto-Gari throw, compared to those that occur at the front during an Ippon-Seoi-Nage throw. More reduction in impact force at the back of the head can be attributed to the shape of the occipital region of the NOCSAE headform, which closely resembles the human skull. This region has a flatter geometry compared to the front, allowing the impact forces to be spread over a larger contact area. (Caccese et al., 2014; Luo & Liang, 2017; MacAlister, 2013). These outcomes highlight the importance of combining head impact locations with under-mat system compliance to minimize head injuries in Judo, particularly during back falls training, where athletes are taught to maintain neck flexion as a preventative measure (Hashimoto et al., 2015; Kanō, 1994). With the addition of a proper under-mat system, such as pool noodles and hockey pucks, it will be safer to train the athletes for breakfalls and neck flexion by mitigating force impact to the head (Murayama et al., 2013),

In contrast, head impacts during Ippon-Seoi-Nage throws involve the front part of the head, which is not smooth compared to the back of the head, leading to localized forces with a higher magnitude than Osoto-Gari throws (Mertz, 1984; NOCSAE®, 2025; Vacca et al., 2020). In the current study, the Ippon-Seoi-Nage throw demonstrated significantly higher impact forces compared to the Osoto-Gari throw. Additionally, there were notable differences in impact forces between the various under-mat systems. For instance, the pool noodle and hockey puck systems showed significantly higher impact forces than the baseline and insulation materials. Although the pool noodle and hockey puck systems are expected to provide more comfort due to their increased compliance, both systems reached a densification point during the Ippon-Seoi-Nage throws. This densification point is the stage at which the material becomes too stiff to absorb a significant amount of energy, leading to an increase in force with minimal deformation of the under-mat system (Xiao et al., 2022). The insulation system, on the other hand, demonstrated

lower impact force for the Ippon-Seoi-Nage throws simulations relative to the baseline under-mat system. This outcome indicates that the insulation under-mat system seemed to be operating within its optimal force absorption range without reaching its densification point for the Ippon-Seoi-Nage throws simulations in this study. More specifically, the impact force was not high enough to compress the material beyond its plateau region (Luo & Liang, 2017).

These outcomes support the result of the static testing that an under-mat system with a low stiffness such as the pool noodles, which absorbed more energy per joule of loading energy than the hockey pucks and it required less force to deform the material to the same amount of displacement as shown in Figures 22 and 23, may provide more comfort during dynamic impacts such as Osoto-Gari Judo throw. This type of under-mat system, however, minimizes the impact force as long as this force does not exceed the viscoelastic properties of the under-mat system beyond its plateau region as in the case of Ippon-Seoi-Nage Judo throws (Ramirez & Gupta, 2019). These findings are consistent with prior surrogate-head model research, demonstrating that material stiffness and energy-absorbing capacity of protective materials directly affect the magnitude of the impact force to minimize the risk of a head injury and concussion (Foster et al., 2018; Luo & Liang, 2017; Siegkas et al., 2019). The differences between the Osoto-Gari and Ippon-Seoi-Nage impact forces across under-mat systems suggest that the effectiveness of under-mat conditions in reducing impact force may rely on the impact location of the head and the multi-layer of materials used to increase or decrease the Judo mat stiffness and energy absorption. This application of multi-layered material systems, which is similar to advanced helmet designs, could further optimize force impact mitigation by combining materials with distinct mechanical properties to address diverse impact scenarios in the sport of Judo (Caccese et al., 2014).

**Linear Acceleration.** Judo athletes experience different magnitudes of linear impact acceleration, particularly on the head, due to the dynamic and high-intensity nature of the Judo throws. As a result, the only injury mitigation strategies are the under-mat system and the athlete's ability to minimize the impact during the fall (Rowson & Duma, 2013). With high linear acceleration at the time of head impact, the brain experiences compression and tension forces within itself. Theoretically, materials with greater energy-dissipating capabilities can decrease linear acceleration by increasing the time over which the impact force is applied (Luo & Liang, 2017).

The results of the current study indicate that the addition of an under-mat layer can effectively attenuate linear impact acceleration transmitted to the head, regardless of the type of Judo throw, as seen in other studies (Sánchez-Sánchez et al., 2019; Shimizu & Yoshitani, 2019; Stitt et al., 2022). Among the tested materials, the largest reduction in head acceleration was observed with the pool noodle system followed by the hockey puck and insulation under-mat systems, suggesting that compared to the baseline, these under-mat systems provided a cushioning effect in minimizing the amount of linear acceleration transmitted to the head, which is known to cause compression and tension across the human brain, leading to intracranial hematomas and concussions (Sánchez-Sánchez et al., 2019; Shimizu & Yoshitani, 2019). Materials with high cushioning abilities, such as the pool noodle under-mat system, for example, are often ideal until they reach a maximum densification point, in which the material no longer provides protection (Tian et al., 2024).

In this study, the relatively lower stiffness of the under-mat systems as compared to the baseline, however, helped reduce the linear impact acceleration transmitted to the head, regardless of the type of Judo throw. Although the force analysis indicated that the under-mat

systems reached saturation during the Ippon-Seoi-Nage impact simulation, the head acceleration data did not exhibit a similar effect. This discrepancy may be attributed to the mechanical neck's dynamic response. As the head form contacted the mat, the mechanical neck continued to flex until the drop carriage reached a complete stop. This delayed motion likely redistributed part of the impact energy through the neck linkage, thereby reducing the peak linear acceleration measured at the head, even though the mat itself had reached its force absorption limit.

This complex relationship between stiffness and cushioning underscores the design trade-offs required for under-mat systems. Optimizing an under-mat system for maximum reduction in head linear acceleration must be balanced against maintaining sufficient structural integrity to prevent excessive deformation of the under-mat systems or bottoming out under high loads (Habegger et al., 2024). This balance is particularly critical in sports such as Judo, where athletes frequently experience low and high-magnitude impacts. Therefore, an effective under-mat system must be capable of mitigating forces across a broad spectrum of impact severities while preserving consistent performance and safety (Caccese et al., 2014).

***Angular Acceleration.*** Every Judo technique involves rotational acceleration when completing a throw. Rotational acceleration relates to the angular motion of the head around its center of mass during an impact, causing shear deformation within the brain tissue and consequently a concussion (Davis et al., 2023; Meaney & Smith, 2011). Both Osoto-Gari and Ippon-Seoi-Nage Judo techniques generate high levels of angular acceleration to complete the throw (Murayama et al., 2014, 2019; Vacca et al., 2020). The Osoto-Gari throw produces a high level of rotational acceleration to the uki during the falling period. The Ippon-Seoi-Nage throw generates a high level of rotational acceleration throughout the throw and fall period on both the uki and tori (Henry, 2011; Rowson & Duma, 2013).

The lack of preparation of the uki when falling during the Osoto-Gari throw, combined with the tori's twisting and bending of the hip during the Ippon-Seoi-Nage throw, significantly contributes to the angular acceleration observed in the head when practicing the sport. Murayama et al. (2014) found that the Osoto-Gari throw demonstrated rotational head acceleration reaching a value between 4284.2 and 5525.9  $\text{rads/s}^2$ . The current study, although it was based on a simulation of Judo throw types, revealed a similar trend, showing a significantly higher average rotational acceleration of 4665.97  $\text{rad/s}^2$  during the Osoto-Gari throw simulation compared to the average rotational acceleration of 3558.91  $\text{rad/s}^2$  for the Ippon-Seoi-Nage throw, regardless of the under-mat system used.

Some researchers, however, believe that the deformation of the under-mat system during a head impact when practicing the sport of Judo may offer an avenue to mitigate rotational acceleration to reduce the risk of concussion. Murayama et al. (2013), for example, examined the angular acceleration values during Osoto-Gari and found a decrease in head acceleration with the addition of an under-mat system. Murayama et al. (2014) conducted another study following a similar methodology to examine the differences in rotational acceleration between under-mat and no under-mat conditions, but the results revealed no significant differences between the two conditions. The results of the current study, however, revealed a significant main effect of under-mat condition, with the pool noodle significantly reducing the angular acceleration induced to the head when compared to the baseline and insulation. The hockey pucks also seemed to reduce the angular acceleration significantly when compared to the insulation. The difference observed between the current study and the findings of Murayama et al. (2014) may be attributed to variations in the anthropometric test devices and data collection methodologies employed in both investigations. The current study utilized a surrogate head form dropped from various precise

heights to simulate the variability among Judo athletes in order to explore differences between under-mat systems. In contrast, Murayama et al. (2014) employed an ATD, which was thrown multiple times by a single Judo expert. This approach is limited to the performance of one individual and fails to capture the population variability of Judo athletes.

The results of the current study underscore that using an under-mat system reduces rotational impacts, which may diminish the risk of concussions. Furthermore, it highlights the safety of under-mat systems for training Judo athletes. One potential application is during breakfall training techniques to further minimize impact rotational accelerations and control energy loading in the head during the contact time (Murayama et al., 2020; Shimizu et al., 2019).

While the reductions of angular acceleration in the current study with the use of pool noodles and hockey pucks under-mat systems seem promising as an avenue to reduce brain tissue damage and consequently concussions in Judo athletes (Meaney & Smith, 2011), further investigation into material properties and supplementary strategies, such as neck strengthening are needed to achieve clinically meaningful concussion mitigation due to angular impacts (Caccese et al., 2014).

***Risk of Head Injury.*** HIC and AGSI are critical measurements for assessing brain injury risk based on measures of linear and rotational accelerations. These measurements provide a greater insight into the likelihood of concussions and TBIs by quantifying thresholds at which a brain injury is probable (Rowson & Duma, 2013). Understanding the impact accelerations that lead to head injury risk allows for the development of more effective protective strategies and equipment, particularly in high-impact sports such as Judo (Caccese et al., 2014). For example, the pool noodle system showed the largest HIC reduction, suggesting its strong capacity to mitigate overall linear energy transfer. It allows for evidence-based recommendations on which

under-mat systems are most effective in reducing the linear component of head impacts, thereby contributing to rule development and facility standards.

**HIC.** The HIC values measured for the pool noodle, hockey puck, and insulation configurations were significantly lower than those recorded for the baseline. Large differences in risk of head injury were observed between the pool noodle and baseline, followed by the difference between the baseline and hockey pucks, which highlights their capacity to attenuate head injury risk while providing more cushioning to athletes during the fall. When comparing these two under-mat systems, it appears that the pool noodles better mitigate risk of head injury due to linear impact; yet the hockey pucks appear to provide better protection in situations when the compliance range of the pool noodles gets compromised due to the magnitude of impact, and it reaches its densification point (Tian et al., 2024).

This outcome suggests that combining effective under-mat systems with proper falling techniques could potentially reduce the overall risk of head injury in Judo for linear impacts (Murayama et al., 2013). The integration of protective strategies is particularly relevant in Judo to reduce HIC given the high head linear accelerations generated during the throws, even with break falls (Florentin & Henry, 2017).

The significant reduction observed with the pool noodle system suggests its ability to mitigate the energy transfer to the head during simulated falls, thus providing an avenue to lowering the potential for severe brain injuries and skull fractures in the sport of Judo (Cobb et al., 2015). More specifically, the pool noodle under-mat system demonstrated a larger reduction in HIC compared to the baseline during the execution of Osoto-Gari throws. This outcome supports the rationale that the efficacy of protective systems is gauged by their capacity to manage impact accelerations to minimize the risk of head injuries in sports (Carlson et al., 2016).

**AGSI.** The results of the current study revealed that the Osoto-Gari throw produced a higher angular risk of head injury than the Ippon-Seoi-Nage throw based on the rotation of the head during the impacts. During a Judo throw, Osoto-Gari inherently generates higher angular acceleration because of the sudden pull of the leg that often prevents the uki from preparing for the fall. This lack of preparation leads to a less controlled descent, potentially causing the head to impact the mat at an angle, generating greater rotational acceleration. As stated by Liu et al. (2025), the sweeping motion of Osoto-Gari might impart more rotational momentum to the uki's body and, consequently, their head, compared to other throws.

Conversely, for the Ippon-Seoi-Nage throw, the tori attempts to throw the uki over their body by twisting and bending at the hips (Kanō, 1994). With this type of throw, there is a more guided or constrained rotation, potentially allowing for some energy dissipation through the tori's body or a more predictable impact angle, leading to comparatively lower angular accelerations (Palavani et al., 2024).

While the results of the current study support previous research on rotational impacts and risk of head injury, the present study is based on fall simulations of a Judo throw. The differences observed between the two Judo throws in the present study are likely related to the geometry of the head and the orientation of the neck (Elkin et al., 2019). In the Osoto-Gari throw simulation, the back of the head struck the under-mat system while the neck was in an extended position. Since the surrogate head is flatter in shape at the back location, it reduces tangential sliding at impact while increasing rotational torque on the neck, consequently raising the risk of head injury (Cobb et al., 2016; MacAlister, 2013). In contrast, during the Ippon-Seoi-Nage throw, the front of the surrogate head impacted the under-mat system, while the neck was in a flexed position. The rounded shape of the head in the front location increases tangential sliding at

impact while decreasing rotational torque, leading to a lower risk of head injury (Cobb et al., 2016; Elkin et al., 2019; MacAlister, 2013).

These outcomes, however, highlight that the type of Judo throw influences the risk of head injury from rotational impacts, regardless of the under-mat system used. The observed AGSI values in Osoto-Gari and Ippon-Seoi-Nage simulation throws emphasize the necessity of evaluating injury predictors that account for not only linear acceleration but also rotational acceleration as a significant factor in brain injury prediction (Caccese et al., 2014; Murayama et al., 2014).

The result also revealed differences in AGSI measures between under-mat systems regardless of the type of Judo throw. These differences suggest that current under-mat systems seem to reduce the risk of head injury due to rotational accelerations. While none of the under-mat systems differed relative to the baseline, differences were found between the pool noodle and insulation, as well as between hockey pucks and insulation. These results imply that while the under-mats may reduce the risk of head injury due to rotational motion, the inherent rotational accelerations generated by the throw type may be a more dominant factor in determining the overall angular injury risk than the specific mat system. The pool noodle under-mat system, for example, seemed to offer some benefits in reducing AGSI values during simulated falls compared to the insulation system; however, this reduction was not significantly different from the baseline system.

The results of the current study are in line with Murayama et al. (2013); however, in both instances, considerations regarding novice neck strength were not included. Further research should include neck strength information from novice and advanced Judoka to provide greater insight into injury risk due to rotational movement, especially given that novice athletes typically

have weaker neck strength (Kamitani et al., 2018; Koshida et al. 2017; Nakanishi et al., 2021; Tsushima et al., 2018).

Overall, these findings provide a greater understanding of how different under-mat materials perform under varied dynamic loading scenarios. The results underscore the importance of developing advanced mat designs that specifically target the reduction of rotational acceleration, potentially through multi-layered systems.

### **Human Participant Testing**

For this test, the researcher used a human tori performing the Osoto-Gari Judo technique on a throwing dummy to replicate the head impact that a uki would experience during a fall. This approach allowed the researcher to provide some evidence of ecological validity to the study while eliminating the risk that a human Judo athlete would encounter during a real throw. Furthermore, this method allowed the researcher to simulate and compare the possible head impact forces experienced by a uki under various mat conditions, including the baseline, pool noodles, hockey pucks, and insulation. This approach is similar to the one implemented by Murayama et al. (2013), which looked into the rotational acceleration of a uki when being thrown with the Osoto-Gari technique.

The study conducted by Murayama et al. (2013), however, only looked at the differences between under-mat and no under-mat systems regardless of the specific material properties of under-mat systems or the role they play in minimizing the risk of head injury. While this approach allows the researcher to examine the effect of an under-mat system, it limits the comprehensive understanding of how specific under-mat systems influence impact force reduction based on their material properties to possibly minimize concussion risk (Luo & Liang,

2017). In contrast, the current research study investigated the influence of various under-mat systems on measures of impact forces and head injury metrics, thereby addressing a critical knowledge gap concerning their protective capabilities during the Osoto-Gari Judo throwing technique.

The findings from the descriptive statistics suggest that the baseline condition exhibited the highest impact force. The impact force, however, decreased for the pool noodles, followed by the hockey puck and insulation under-mat systems. These findings seem to support the results of the static and simulated dynamic head collisions, which highlight that while the baseline absorbed the most energy during static compression, the high stiffness properties of the baseline material did not allow the Judo mat to deform quickly enough to mitigate the impact force, consequently increasing the impact force experienced by the uki's head (Tian et al., 2024). The pool noodles, however, seemed to reduce the magnitude of the impact force due its compliance properties but because inferential analysis was not conducted for this testing, it is not possible to know if the pool noodle reached the densification point of the material, compromising its capability to mitigate impact force during the head dynamic impact simulations of the human participant testing (Xiao et al., 2022).

The outcome of the human participant testing, however, seems to support the results obtained from the force measures of the dynamic simulation testing for the Osoto-Gari Judo throw, where the pool noodle and hockey pucks performed better than the other under-mat systems. Some of the differences seen on the outcome measures between the two tests with respect to the other under-mat systems can be attributed to the human variability introduced during the throwing trials. For example, the head impact angle during the human throwing trials may have differed slightly between trials compared to the controlled flexion angle seen during

dynamic head impact simulations. Furthermore, the Fuji head and neck were much softer and lighter compared to the NOCSAE© head form, which might have influenced the impact force seen. As stated by Murayama et al. (2013), the benefits of involving anthropomorphic test devices that are capable of measuring both linear and angular accelerations during falls are that the researcher can accurately replicate real-world impact events, such as those experienced by a uki during a Judo throw. In addition, the Fuji dummy did not allow for controlled neck strength to provide a better insight into head injury prevention (Kamitani et al., 2018; Tsushima et al., 2018) as compared to the dynamic simulation test, where the neck strength level was controlled with the mechanical neck.

The results of the current study, which included static, dynamic simulations and human throwing trials, seem to indicate that while the pool noodles perform well for the Osoto-Gari throwing techniques based on head impact simulations, they are less effective for the Ippon-Seoi-Nage throws. Although, a hockey puck under-mat system is stiffer than the pool noodles, it may be more effective in accommodating the Ippon-Seoi-Nage and Osoto-Gari throwing techniques to better prevent risk of head injury and concussions. Finally, while the insulation under-mat system seems to mitigate impact forces and acceleration during the impacts better than the other under-mat systems, its inability to return to the original shape after deformations, makes it less attractive to be implemented as an effective under-mat system in Judo clubs.

## Chapter 6 - Conclusion

Overall, the present study highlights that under-mat systems play a significant role in reducing impact forces and accelerations, thereby minimizing the risk of head injuries in Judo. This outcome addresses a notable gap in prior research by demonstrating the effectiveness and potential of the under-mat system in head injury prevention. However, performance varies among under-mat systems and testing conditions. While static testing indicated that the baseline and insulation systems had high energy absorption but stiffer material properties, dynamic testing revealed that the pool noodle and hockey puck systems consistently yielded lower peak forces, accelerations, HIC, and AGSI values.

These outcome measures suggest that the baseline requires a very high force and consequently higher linear impact acceleration to deform, which translates into a high level of stiffness as compared to the under-mat systems. The human participant testing added more ecological validity to the findings, suggesting that the under-mat systems absorbed more force than the baseline.

In terms of mitigating the risk of head injury, the pool noodle performed better than the under-mat systems followed by the hockey pucks. However, when considering overall human safety, the pool noodle has limitations in its protective capabilities when the material reaches its limits during high impacts, such as those experienced by Judo athletes during Ippon-Seoi-Nage throws, potentially compromising its capability to provide protection.

When putting all the evidence together, it points out that the hockey pucks, while more expensive to implement, seem to provide a better option for the safety of the Judo athletes in mitigating the risk of head injury and concussions. In summary, this study emphasizes the

necessity of employing comprehensive methodologies, including static testing, dynamic simulations and human participant testing, to more accurately assess the protective capabilities of under-mat materials in complex biomechanical scenarios. As such the researcher accepts the hypothesis that the pool noodle would see the least amount of energy absorption during static testing but the greatest reductions in impact force, linear acceleration, angular acceleration, HIC and AGSI values during dynamic testing. The researcher also rejects the hypothesis that the pool noodle system would have the greatest force absorption during human participant testing.

### **Strengths**

This study's primary strength lies in its innovative integration of both static material testing and dynamic simulations to comprehensively evaluate under-mat systems, addressing a notable gap in prior research that often overlooked the specific material properties and their influence on head injury risk (Luo & Liang, 2017). The inclusion of both dynamic drop simulations and human participant simulations allowed for a robust assessment of real-world impact scenarios. Thus, allowing the research to observe the role human variance may play in the simulations. The comparison between the under-mat behaviours during static and dynamic testing also allowed for a more holistic approach to understanding the complex interplay between material characteristics and head injury risk.

Furthermore, the study utilized commonly seen under-mat systems that are readily available and cost-effective, providing practical and implementable solutions for Judo clubs. To further mimic a Judo club setting, the researcher focused on common high injury risk throws (Osoto-Gari and Ippon-Seoi-Nage) that often result in head injuries. Aimed at creating an all-encompassing testing environment. This comprehensive methodology allowed for a detailed

analysis of force reduction mechanisms and the effectiveness of different under-mat materials in mitigating impact forces, which are seen in Judo training and competition.

### **Limitations**

Despite these strengths, the study had several limitations that warrant consideration for future research. Specifically, the reliance on a single throwing dummy to simulate the uki during human participant testing, while mitigating direct human risk, may not fully capture the biomechanical variability inherent in actual human falls, potentially limiting the generalizability of the dynamic impact data (Caccese et al., 2014). Additionally, the use of a Fuji throwing dummy opposed to an anthropometric test device may not accurately replicate the complex head and neck kinematics of a human, potentially affecting the precision of impact force measurements (Cobb et al., 2015). The addition of an anthropometric test device equipped with advanced sensors could provide more accurate and detailed data on linear and angular accelerations, crucial for comprehensive head injury assessment (Payne et al., 2014). Furthermore, an anthropometric test device could provide more controlled segmental mass to ensure that the weight of the head and neck strength are consistent throughout trials. Further investigation with such devices is necessary to characterize the role of landing coordination and its relation to mat characteristics to fully understand and later optimize landing strategies in Judo, much like similar research in gymnastics (Crolan et al., 2022).

Moreover, while the study focused on commonly used low-cost under-mat systems, it did not explore marketed under-mat systems or less common systems. Given the lack of regulations associated with under-mat systems, this omission represents a potential gap in understanding the full spectrum of available protective solutions. It also did not consider the long-term degradation or performance changes of these materials under repeated impact, which could significantly

affect their protective capabilities over time and lead to a gradual reduction in force absorption and an increased risk of injury.

### **Future Research**

Future research should, therefore, explore multi-layered under-mat systems that integrate both compliant and stiff materials to optimize force attenuation across a wider range of impact energies and provide comprehensive protection for Judoka (Beránek et al., 2024). This approach could draw inspiration from helmet designs that combine materials for linear acceleration attenuation with those that control rotational forces, offering a more holistic protective solution.

Future research should utilize anthropomorphic test devices capable of measuring a wider range of biomechanical parameters, including rotational accelerations, to more precisely evaluate injury risk when completing the Osoto-Gari Judo technique on a throwing dummy (Luo & Liang, 2017). The additional parameters could significantly enhance the understanding of brain injury mechanisms by providing a more comprehensive dataset for injury risk assessment in dynamic impact scenarios (Preatoni et al., 2022). A more comprehensive dataset would allow for the development of more accurate predictive models for head injury risk in sports like Judo, where rotational forces play a significant role and techniques are repeatedly performed with varying intensities.

Future research should explore the differences in neck strengths between novice and advanced level judoka with regards to under-mat systems. This research could examine how varying neck musculature and control affect head and neck kinematics during impact, and how these factors interact with different under-mat systems to mitigate injury risk, especially given that age-related differences in neck strength have been linked to head and neck injuries in

judokas under 20 years of age (Kamitani et al., 2013). Furthermore, the role of neck strength in mitigating head rotational acceleration during falls is a critical area for investigation, particularly given that current research indicates rotational acceleration as a primary contributor to severe brain injuries (Ishikawa et al., 2018; Murayama et al., 2014; Tsuyama et al., 2001).

Understanding these interactions could lead to targeted training interventions and material development that enhance protective strategies for judoka across all experience levels.

Additionally, investigating the long-term material performance and degradation of undermat systems under repeated impact cycles would provide crucial insights into their sustained efficacy and possible injury risk (Mass et al., 2022). Given that many Judo clubs will install these systems and not replace them, it is important to understand how their protective capabilities change over time, especially considering the high frequency of falls in Judo training. This additional consideration could inform recommendations for maintenance schedules and replacement guidelines to ensure optimal safety for Judo clubs (Caccese et al., 2014; Reynolds et al., 2016).

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## Appendix A

### Summary of Dynamic Results

Baseline				
Variable	Osoto-Gari		Ippon-Seoi-Nage	
	Mean (N)	Standard Deviation	Mean (N)	Standard Deviation
Resultant Force	875.53	206.179	978.476	123.097
Linear Acceleration	71.532	27.105	60.105	29.235
Angular Acceleration	4775.75	2236.697	4777.86	2963.079
HIC	186.07	116.9	135.52	113.68
AGSI	658.09	433.69	1085.28	1124.82

Pool Noodle				
Variable	Osoto-Gari		Ippon-Seoi-Nage	
	Mean (N)	Standard Deviation	Mean (N)	Standard Deviation
Resultant Force	831.98	254.237	1040.335	195.246
Linear Acceleration	43.895	12.824	29.653	12.47
Angular Acceleration	4045.552	1969.847	2684.653	569.102
HIC	66.57	46.97	36.3	29.84
AGSI	854.19	722.25	318.61	29.84

Hockey Pucks				
Variable	Osoto-Gari		Ippon-Seoi-Nage	
	Mean (N)	Standard Deviation	Mean (N)	Standard Deviation
Resultant Force	870.422	263.652	1055.552	138.124
Linear Acceleration	44.064	17.215	38.636	15.735
Angular Acceleration	4116.119	2288.259	3157.465	730.652
HIC	96.13	74.26	65.89	49.26
AGSI	855.32	873.91	446.44	49.26

Insulation				
Variable	Osoto-Gari		Ippon-Seoi-Nage	
	Mean (N)	Standard Deviation	Mean (N)	Standard Deviation
Resultant Force	862.684	247.559	983.711	136.012
Linear Acceleration	51.789	20.422	47.482	23.832
Angular Acceleration	5726.471	2884.22	3615.666	1838.947
HIC	116.53	85.98	96.9	81.54
AGSI	1561.57	1206.54	1046.45	81.54