9-20-2022 3:45 PM

Determination of the Protective Capacity of Hand Wraps in Combat Athletes Using Force Analysis

Eva M. Gusnowski, *The University of Western Ontario*

Supervisor: Grewal, Ruby, *The University of Western Ontario*
Co-Supervisor: Faber, Kenneth, *The University of Western Ontario*
Co-Supervisor: Langohr, Daniel, *The University of Western Ontario*
A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Surgery

Abstract

Upper extremity injuries are common in combat athletes, and are highest in the hand/wrist. Although protective hand gear is used, there is a paucity of research investigating its effectiveness. This study addressed this knowledge gap by measuring the level of force transmitted to the hand during striking using two types of hand wraps. This prospective cross over study included six combat athletes. A load cell was placed over the proximal phalanges/metacarpophalangeal joints and was used to measure sustained peak force during striking while covered with either standard linear or gel-reinforced hand wraps and boxing gloves. The gel reinforced wraps consistently had a lower level of force measured at the hand in all six athletes. This finding was more pronounced in athletes with higher experience levels. These results suggest that combat athletes should utilize modern hand wraps with gel reinforcement to absorb impact and provide improved hand protection.

Keywords: combat athlete, hand, wrist, force, load cell

Summary for Lay Audience

Combat sports are one of the most popular and universally trained athletic disciplines. Upper extremity injuries constitute the second most common site of injury in boxers, the third most common site of injury in mixed martial artists, and is highest in the hand and wrist. Proper striking technique directs force from a punch down the wrist and forearm, whereas poor technique can result in abnormal forces across the hand and wrist and can result in significant hand and wrist injury. Additionally, repetitive impact on the surface of the hand can also result in chronic injury. Taken together, this suggests that absorbing impact at the surface of the hand could prevent injury in combat athletes.

Although protective hand gear is often used in a variety of combat sport practices, there is little research investigating its ability to absorb force and protect the athlete's hands. This study aims to address this knowledge gap by measuring the level of force that is transmitted to the hand and wrist during striking using two commonly used types of hand wrap protection.

This study included six combat athletes. A force sensor was placed over the fingers and was used to measure how much force was transmitted to the hand during striking while covered with either standard linear or gel-reinforced hand wraps and boxing gloves. The gel reinforced hand wraps consistently absorbed more force at the hands compared to the standard linear hand wraps. This finding was more pronounced in athletes with higher experience levels.

These results suggest that combat athletes should use modern hand wraps with gel reinforcement to absorb impact and provide improved hand protection.

Co-Authorship Statement

Chapter 1:

Manuscript preparation – Eva M. Gusnowski

Manuscript review – Ruby Grewal, Kenneth Faber, Daniel Langohr

Chapter 2:

Study design – Eva M. Gusnowski

Primary paper review – Eva M. Gusnowski

Secondary paper review – Manisha R. Mistry

Manuscript preparation – Eva M. Gusnowski

Manuscript review – Ruby Grewal, Kenneth Faber, Daniel Langohr

Chapter 3:

Study design – Eva M. Gusnowski, Gregory Spangenberg, Daniel Langhor

Data collection – Eva M. Gusnowski, Gregory Spangenberg, Daniel Langhor

Data analysis – Eva M. Gusnowski, Gregory Spangenberg, Daniel Langhor

Manuscript preparation – Eva M. Gusnowski

Manuscript review – Ruby Grewal, Kenneth Faber, Daniel Langohr

Chapter 4:

Study design – Eva M. Gusnowski

Data collection – Eva M. Gusnowski

Data analysis – Eva M. Gusnowski, Gregory Spangenberg, Daniel Langhor

Manuscript preparation – Eva M. Gusnowski

Manuscript review – Ruby Grewal, Kenneth Faber, Daniel Langohr

Chapter 5:

Study design – Eva M. Gusnowski

Data analysis – Eva M. Gusnowski

Manuscript preparation – Eva M. Gusnowski

Manuscript review – Ruby Grewal, Kenneth Faber, Daniel Langohr

Dedication

Dedicated to LL Cool J

because

Mama said knock you out

Acknowledgements

I would like to acknowledge the contributions of my co-authors and thesis committee members throughout this thesis and their assistance to the completion of this work.

This thesis would not have been possible without the support of my family, friends and colleagues who encouraged me along the way.

I would also like to acknowledge the athletes who not only contributed to this thesis but to the gyms, coaches and fighters who inspired its completion. This work is for everyone who has been fighting in the shadows or the spotlight.

Table of Contents

List of Figures

List of Tables

List of Appendices

Chapter 1. Introduction

1.1 Introduction to combat sports

Combat sports are one of the most popular and widely televised sporting events. The four Ultimate Fighting Championship (UFC) pay-per-view preliminary fight cards taking place during 2020 (UFC 249 in Jacksonville, Florida, on May 9; UFC 250 in Las Vegas on June 6, 2020; UFC 251 in Abu Dhabi on July 12, 2020; and UFC 252 in Las Vegas on August 15, 2020) averaged 1.173 million viewers across ESPN and ESPN+ platforms, increasing 30% from televised pay-per-view events in 2019.(1) In addition to professional matches and viewership, combat sports are a globally trained athletic discipline. This catch-all term encompasses a wide spectrum ranging from cultural practices to modern mixed martial arts to warfare training of hand-to-hand combat techniques used in modern military systems. This includes striking sports, such as boxing and Muay Thai, and positioning and throw sports such as jiu jitsu and aikido. Many combat sports use a spectrum of striking, holds and throws, including karate and mixed martial arts. Combat sports involve a high degree of discipline, dedication and ability in order for athletes to actively compete at a professional level. For the amateur and public population, these sports provide a highly beneficial exercise regimen with proven physical and psychological benefits, either with or without participation in fighting matches.

1.2 Health benefits of combat sports and related practices

1.2.1 Musculoskeletal health benefits of combat sports and related practices in the elderly population

Exercise programs including weightbearing, resistance, balance and flexibility have been associated with a decreased risk of falls and an increase in bone mineral density in osteoporotic women.(2) Institution of Tai Chi and Qigong practices, which focus on balance and flexibility, have been shown to improve balance, decrease risk of falls and increase balance confidence in the older adult population.(3) The positive effect of training is not limited to weight bearing bones; a prospective, cross-over design study instituting 1 year of Tai Chi practice demonstrated improvement in bone mineral density in the phalanges of women when tested via quantitative ultrasound.(4) An adapted karate training program was found to improve lower extremity strength, as well as functional autonomy and mental health scoring in an elderly male with osteoporosis.(5) Institution of a 3-month Ving Tsun Chinese martial arts training program in a prospective cohort of elderly participants demonstrated a trend towards an increase in grip strength, radius bone mineral density and shoulder mobility compared to a non-intervention group.(6) Biomechanical studies have also investigated the use of martial arts falling techniques as an intervention to decrease load onto the greater trochanter during a fall from kneeling or standing height, which is one of the major causes of hip fractures in the elderly population. The use of martial arts falling techniques was found to decrease the impact force transmitted to the greater trochanter with a fall from kneeling height by 27% without changing the point of impact, whereas these techniques changed the point of impact when the fall was from standing height.(7)

1.2.2 Musculoskeletal health benefits of combat sports and related practices in healthy adolescents and adults

Musculoskeletal benefits of combat sport training are not limited to the older population, and have also been demonstrated in healthy adolescent and adult participants. A systematic review demonstrated a positive correlation between combat sport participation and bone mineral density in both healthy adolescents and adults.(8) In a prospective trial in adolescent males, Violan et al. (1997) demonstrated that 6 months of a twice weekly karate training program resulted in improvement of quadriceps and hamstrings strength and flexibility, as well as improvement in overall balance compared to age-matched controls.(9) Participation in taekwondo by adolescent Korean females was also found to result in significantly higher lumbar spine bone mineral density as measured by dual-emission X-Ray absorptiometry (DEXA) compared to sedentary age and weight matched controls.(10) Judo specific interval/circuit training in adolescents has been shown to produce maximum heart rate and oxygen consumption levels on par with running or cycling.(11) A 9-month long judo training program in 7-year-old males resulted in a statistically significant increase in improvement in the shuttle-run test of agility, sit-up test for abdominal muscle endurance and the sit-to-reach test for flexibility compared to an age-matched cohort participating in group recreational sports (minisoccer, minihandball or minibasketball).(12)

1.2.3 Mental health and combat sport participation

Combat sports are traditionally associated with the pedagogy of violence and aggression, as the nature of the sports are often rooted in battle and war. Even the origin of “martial arts” comes from the Latin expression "from Mars," in reference to the Roman god of war. Despite this, Szabo et al. (2014) hypothesized that athletes in combat sports may have a higher degree of emotional intelligence and lower neuroticism than a cohort of peers that do not participate in combat sports.(13) The group analyzed Hungarian national or international level boxing and judo athletes attending the Central School of Sports in Budapest compared to age-matched non-athlete controls from university psychology students. Participants were provided with two validated psychology questionnaires to assess for extroversion, neuroticism and emotional intelligence. Boxers were found to have significantly lower levels of neuroticism, increased extroversion and increased emotional intelligence compared to the age-matched peers, whereas judo athletes demonstrated increased extroversion and use/regulation of emotions compared to age-matched peers. Conclusions from this study demonstrate that boxing and judo may either foster or attract athletes with these personality traits.

In an analysis of combat sport athlete quality of life, Kotarska et al. (2019) compared three groups of combat sport athletes that either: 1) participated at a recreational level; 2) participated at a competition level; or 3) participated in combat and other sports.(14) This study used the validated World Health Organization Quality of Life–BREF questionnaire in an assessment of the domains of physical, psychological, social and environmental health. The authors found that athletes that were involved in competition were most likely to be involved in healthy patterns of behaviour, were least likely to smoke and had a lower level of alcohol consumption than either of the other groups. Although these questionnaires are subjective, the competitive group also reported the highest quality of life in physical, psychological and environmental domains at a statistically significant level.

1.3 Injuries in combat sports

1.3.1 General risk of injury in combat sports

Despite widespread popularity and increased acceptance in mainstream society, combat sports remain a potentially dangerous endeavour, from both the recreational to the professional athlete. Potential injury sites include face, head and neck, intra-abdominal and musculoskeletal injuries, the frequency of which is related to how a given combat sport is practiced and the level of participation.

1.3.2 Head and neck injury in combat sports

In striking combat sport matches, athletes are rewarded by strikes to the body and head of their opponent. Because of this, a large burden of injury is incurred by the head/neck region, especially in striking dominant sports such as boxing. In a national retrospective survey of United States emergency department records, combat sports (including boxing, mixed martial arts and wrestling) resulted in an estimated/extrapolated 42395 emergency department visits due to head, neck or facial trauma.(15) Out of the recorded visits, 46.0% were due to lacerations, 26.2% were due to fractures and 19.3% were due to contusions or abrasions. Boxing resulted in the highest proportion of facial fractures (36.9%), while mixed martial arts resulted in the highest proportion of facial lacerations (50.4%).

Aside from facial trauma, intracranial trauma is also a concern in combat sports. In a meta-analysis of 8 different contact sports, boxing was found to have the highest incidence of concussion in both professional and amateur athletes in individual sport, however ice hockey athletes had the highest incidence overall.(16) Despite the results in this and similar publications, combat sports continue to have a reputation for high levels of head injury and is discouraged in adolescent and pediatric patients while team contact sports are encouraged.(17) Although head injury is possible, repetitive head trauma in combat and other contact sports is concerning and lies on a spectrum from acute concussion to subdural hematoma, and eventually chronic issues such as dementia puglistica.(18, 19) Significant research effort has therefore been invested in the analysis of brain injuries and cognitive dysfunction in combat athletes, with efforts directed towards injury prevention and treatment.

1.3.3 Upper extremity injury in combat sports

Despite the obvious concern for head and intracranial injury, upper extremity injuries constitute the second most common site of injury in boxers, and the third most common site of injury in mixed martial artists.(20-22) Although the literature reports shoulder, forearm and elbow injuries,(23-27) the most common type of upper extremity injury involves the hand and wrist, encompassing 53-90% of incurred upper extremity injuries.(22, 28, 29) In striking sports such as boxing, hand injuries encompass a wide spectrum from soft tissue injuries, such as rupture of the sagittal band of the extensor tendon hood ("boxer's knuckle"), to carpometacarpal joint dislocations.(29-31) In a survey of 100 consecutive hand/wrist injuries incurred by 86 professional boxers, 69% involved the right hand whereas 31% involved the left hand. Only 15 of the 86 athletes were left hand leading (“southpaw” stance), and these athletes incurred 52% of the left-hand injuries. Out of the injuries, 39% occurred at the thumb, thumb carpometacarpal joint or scaphoid, 35% occurred at base of the index, middle, ring or small finger metacarpals including the wrist joint and remaining carpals, and 26% occurred in the index, middle, ring or small finger metacarpal shaft/head and phalanges.(20)

1.3.4 Risk factors for upper extremity injury in combat athletes

Risk factors for hand and wrist injury in combat athletes include male sex, striking sports, increasing age/experience level and match outcome.(22, 32, 33) Increased experience with a larger number of training years also increases the likelihood of chronic pain secondary to upper extremity injury.(22, 33, 34)

1.3.5 Acute hand and wrist injury in combat sports

The spectrum of hand and wrist injury in combat athletes includes bone, tendon, ligament, skin and nerve injury. The soft tissues of the hand are complex structures that accommodate the independent and complex movements necessary to support hand and wrist function. Documented soft tissue injuries in combat athletes include rupture of the extensor hood and sagittal bands along with extensor tendon subluxation at the level of the metacarpophalangeal (MCP) joint (known as the “Boxer’s knuckle”), which can be due to acute injury or repetitive trauma at the level of the MCP joint.(35) Other soft tissue injuries reported include trauma to the ligament and capsular structures surrounding the interphalangeal joints, intercarpal ligaments, the extensor/flexor tendons and the overlying skin.(29)

Bony injury is also possible in the spectrum of hand and wrist injury incurred in combat sports. This spectrum includes fractures of the fingers, thumb, carpus and wrist, as well as subluxations or dislocations of the interphalangeal, MCP, intercarpal, wrist and distal radioulnar joints.(20) The aptly named “boxer’s fracture,” which commonly occurs secondary to punching in the non-athlete, refers to a fracture to the distal end of the metacarpal neck, most common in the ring and small metacarpals.(36, 37)

1.3.6 Chronic hand and wrist injury in combat sports

Acute injury to the hand and wrist is often a prioritized concern among combat athletes, however these injuries can also result in chronic pain and disability. Repetitive axial load across the hand

and wrist can cause progressive joint instability and articular degeneration. These injuries have the potential to require arthrodesis procedures to allow an athlete to continue to participate in training, matches and daily function.(34) There have been reports of increased radiographic arthritic changes in hip, knee and ankle radiographs in elite male athletes compared to age-matched cohorts, however the clinical findings of arthritis (i.e. decreased range of motion, crepitus and pain) were not different between the two groups.(38) A radiographic study of the hands of 22 karate masters presenting with a hand injury to the emergency department demonstrated evidence of prior fractures (6 of 22 patients), but no signs of early joint space narrowing or carpal bossing outside of one patient with confirmed rheumatoid arthritis. (39) However, inclusion criteria for this study only required 5 years of experience and 13 of the 22 patients demonstrated physical signs of chronic hand/wrist injury (i.e., knuckle pads, thumb ligament instability). Long term chronic hand and wrist injuries are therefore not only possible, but are highly prevalent in combat athletes, if chronic soft tissue and ligamentous injuries are also considered rather than just bony injuries.

1.3.7 Experience level and frequency of training in combat athletes is related to biomechanical parameters and likelihood of injury

Because of the popularity of combat sports, most participants are not professionally trained athletes. Rather, most participants are amateurs that often lack sufficient training in proper technique, which can result in an increased likelihood of individual injury. Teenage male judo participants have improved static and dynamic balance versus their non-judo trained peers.(40) Additionally, expert judo adult athletes have been shown to display different knee biomechanics during break falls when compared to novice athletes.(41) The increased knee extension during the break fall seen in experienced judo athletes has been hypothesized to improve the athlete's control of the fall velocity, which in turn could help to prevent head injury. Taken together, this implies that the level of experience is integral in injury prevention.

Although experience level must be considered, the intensity and frequency of training undertaken by professionals increases their likelihood of injury secondary to increased training volume. Therefore all participants in combat sports, from novice to experienced, face the risk of sustaining upper extremity injury.(29, 42) The global risk of injury for all participants necessitates the institution of appropriate and effective protective gear for training and match purposes.

1.4 Hand and wrist anatomy relevant to combat sports

1.4.1 Bony anatomy of the hand and wrist

The hand and wrist functions as a complex unit in order to facilitate the dexterity and range necessary to complete not only delicate tasks, but gross motor tasks such as power grip. Bony anatomy consists of five rays, comprised of four fingers and the thumb. Each ray includes a metacarpal and 3 phalanges which make up the finger unit (Figure 1.1). The thumb differs as it only contains 2 phalanges in addition to its associated metacarpal. The metacarpals articulate proximally with the distal carpal row (hamate, capitate, triquetrum and trapezoid) at the carpometacarpal (CMC) joints. Additionally, the first CMC joint of the thumb has a specialized saddle shaped articulation allowing for additional degrees of freedom of movement of the thumb.

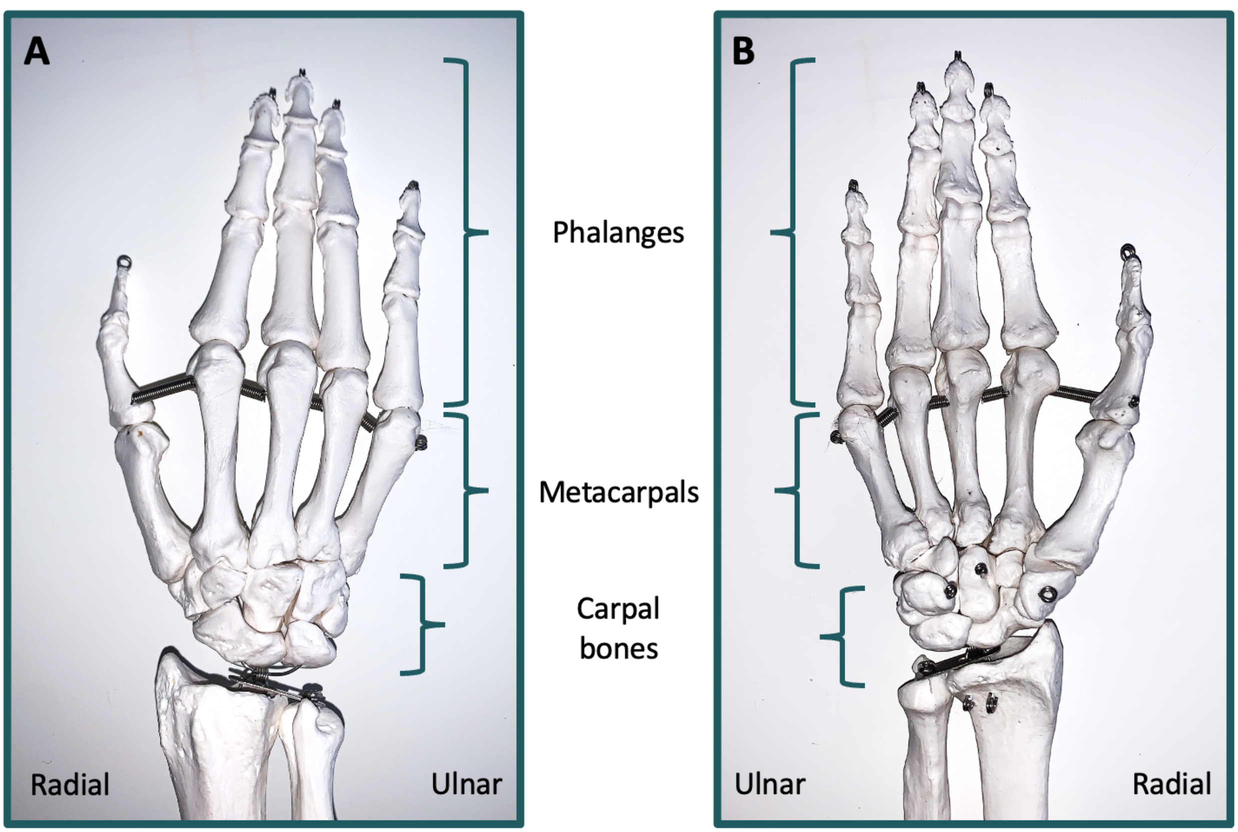

Figure 1.1. Bones of the hand and wrist (right). A. Dorsal surface. B. Palmar surface.

The distal carpal row is connected to the distal radius and ulna of the forearm by the remaining carpal bones of the proximal row (scaphoid, lunate, triquetrum). The pisiform bone is a sesamoid bone of the flexor carpi ulnaris tendon and does not contribute to transmission of force from the forearm to the fingers. Finally, proximally, the distal radius and ulna also articulate at the distal radioulnar joint which allows pronation and supination. (43)

The complex interplay of the carpal bones and associated axes of rotation is beyond the scope of this review, but in and of itself demonstrates a complex interaction between multiple articulations. The interactions between these joints allows the complex motions of the wrist, including flexion, extension, ulnar and radial deviation as well as supination and pronation.

The metacarpals are the longest bones of the hand and each metacarpal is comprised of a condylar head and neck region at the distal end. The head and neck sit in a slightly flexed posture compared to the long axis of the metacarpal shaft. Each metacarpal head also articulates with the proximal phalanx of its respective finger forming the MCP joints. The thumb metacarpal is distinct in its overall position, as it is rotated out-of-plane with respect to the other metacarpals in order to allow thumb opposition.

1.4.2 Soft tissue anatomy of the hand and wrist

Overlying the MCP joint is the extensor hood, which is a dorsal soft tissue structure that allows centralization and appropriate function of the extensor tendon. The integrity of this structure is necessary to allow efficient extension of the MCP and interphalangeal joints (Figure 1.2).

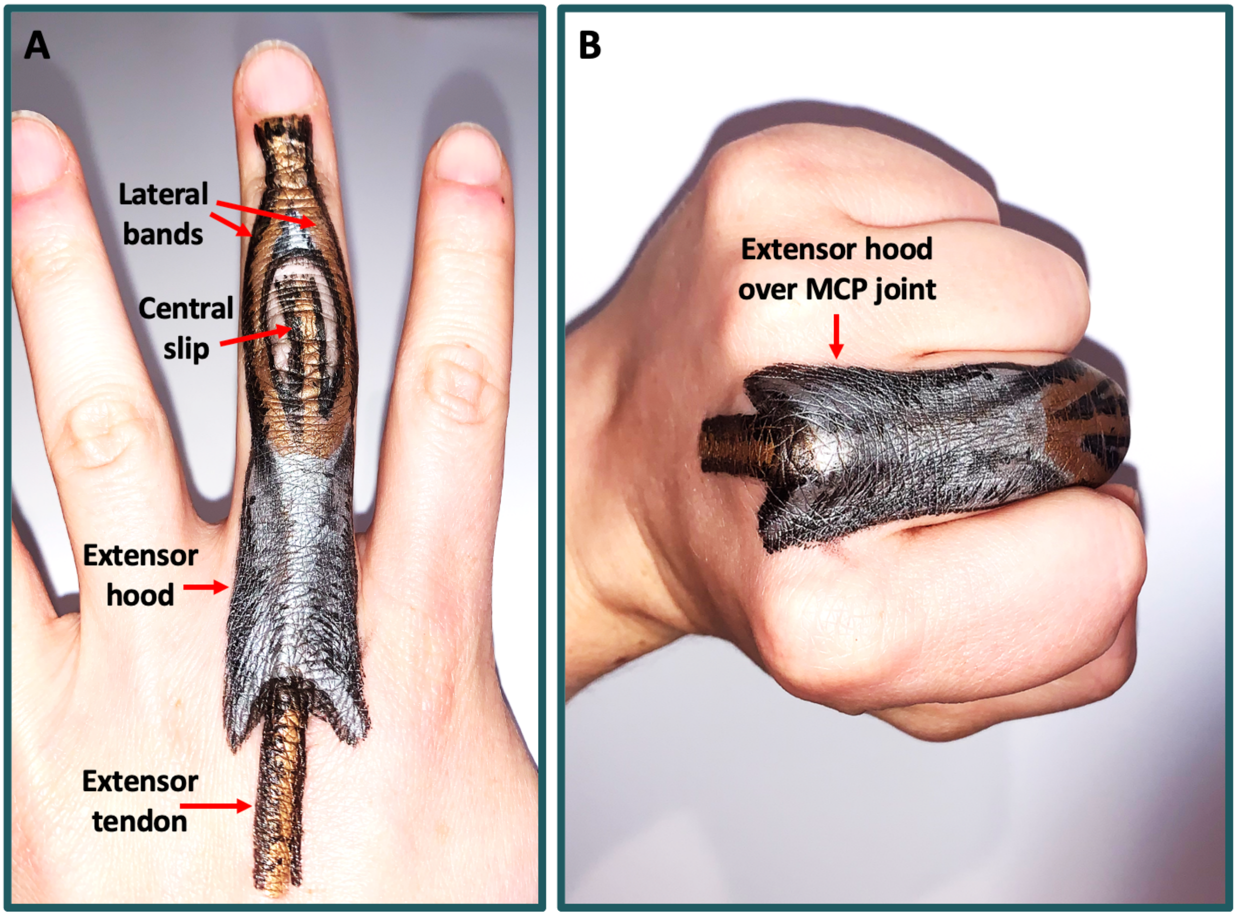

Figure 1.2. Diagrammatic representation of soft tissues along the dorsal middle finger of the left hand. A. Finger in extension. B. Closed fist.

Each interphalangeal joint, including the single thumb interphalangeal joint and the proximal and distal interphalangeal joints of the remaining digits, consists of a circumferential joint capsule and accessory and true collateral ligaments that flank the radial and ulnar sides of each joint. The true collateral ligaments are the most significant stabilizers of these joints. Additionally, the MCP and interphalangeal joints have a volar soft tissue structure, known as the volar plate, that prevents joint hyperextension. Two flexor tendons, the flexor digitorum superficialis and flexor digitorum profundus, lie along the volar surface of each digit (excluding the thumb), and are held in close proximity to the phalanges by a series of annular and cruciate pulleys. This series of pulleys are responsible for efficient flexion of the digits, load distribution and prevention of tendon bowstringing. The primary thumb flexor tendon, flexor pollicis longus, is also held in close proximity to the phalanges by its own distinct series of pulleys. Thumb flexion is also aided by the flexor pollicis brevis tendon which originates and lies within the intrinsic musculature of the hand. At the level of the wrist, volar and dorsal soft tissue structures include the joint capsule and associated ligamentous structures that link the carpal bones to one another as well as to the distal radius and ulna.

The metacarpal heads of the index, middle, ring and small fingers are interconnected by the deep transverse metacarpal ligaments which attach a given metacarpal head to its adjacent counterpart. The thumb metacarpal does not have an associated deep transverse metacarpal ligament.

1.4.3 Relation of hand and wrist anatomy to striking and potential for injury

Proper striking technique directs the force of a punch through the middle finger metacarpal and proximally to a neutrally aligned wrist; deviation from this orientation generates abnormal forces across the hand and wrist and can result in injury.(31) For example, if the wrist is held in a flexed position during a clenched fist strike, this places an increased flexion moment across the dorsal surface of the wrist and can result in stretching and eventual rupture of the dorsal intercarpal ligaments or CMC joint dislocation or fracture. Excessive force placed along the dorsal surface of the metacarpal head and neck can cause fracture or dislocation in this area, resulting in a boxer's fracture or MCP joint dislocation. The opposite holds true when the wrist is held in extension during a strike, with excessive force placed through the volar wrist ligaments and associated soft tissue structures. However, despite proper technique, direct impact across the MCP joints can still result in significant injury due to the overlying complexity of the extensor soft tissues (Figure 1.2). Force applied across the MCP joints, when considered with respect to the normal anatomically flexed posture of the metacarpal head and neck, can generate a flexion moment across the metacarpal neck with force transmission to the bone resulting in a boxer's fracture.(44) Additionally, the unique position and relative rotation of the thumb metacarpal places the thumb at unique risk for injury during gripping motions as well as during strikes which may result in a deviated force vector across the thumb CMC and MCP joints, placing it at high risk for joint subluxation or dislocation.

1.5 Striking/punch biomechanics

1.5.1 Normal closed fist punching biomechanics

In a study including healthy adult male and female volunteers of various experience levels, differences were noted in punch parameters, including maximum force, impulse, duration, velocity and effective mass.(45) Experience level did not increase the velocity of a punch, however the effective mass was found to be significantly higher with increased experience, likely owing to technique rather than raw speed. This implies that training in striking combat sports will likely significantly alter the force biomechanics during striking.

The standard six strikes used in all combat sports include the jab, cross, lead/rear hooks and lead/rear uppercuts (Figure 1.3). The jab and cross are straight punches thrown from the lead and rear hands respectively, in a direct line from the jaw to the target with the forearm in full pronation. The lead and rear hooks are thrown with the shoulder and elbow both at 90 degrees of abduction and the forearm in full supination. The lead and rear uppercuts are thrown with the shoulder partially abducted between 20-45 degrees, the elbow in 90 degrees of flexion and the forearm in full supination.

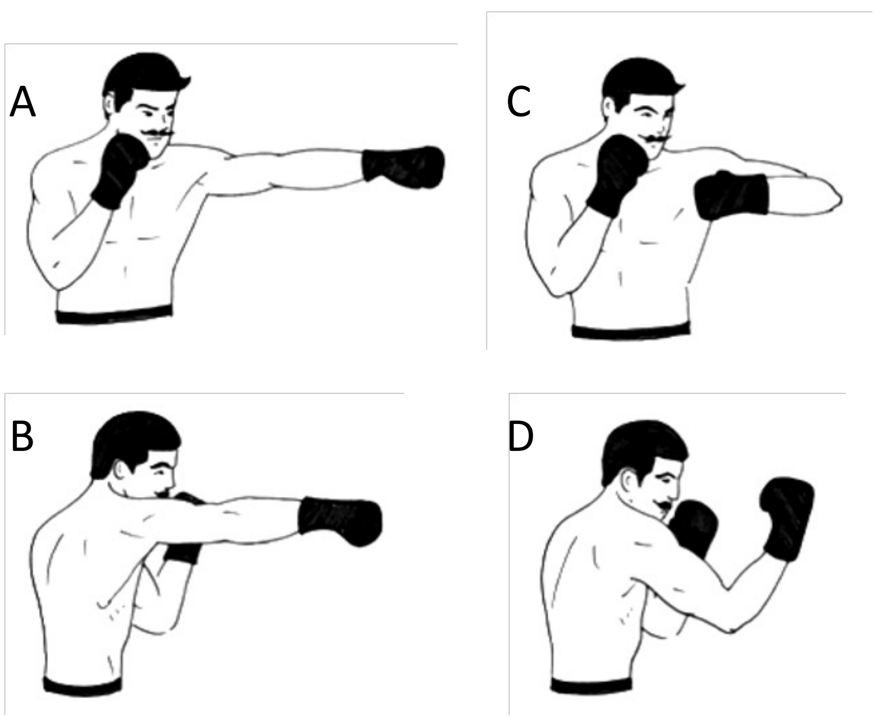

Figure 1.3. Standard hand strikes thrown in combat sports in an orthodox stance. A. Jab. B. Cross. C. Lead hook. D. Rear uppercut. Note that the rear hook and lead uppercut are not demonstrated but thrown in a similar position to C and D above.

1.5.2 Changes in upper extremity biomechanics in experienced boxers

A study performed by Letesky et al. (2015) investigated the shoulder range of motion and scapular kinetic profile in a small cohort of experienced boxers compared to a non-boxing cohort of peers.(46) In the dominant (rear) arm, boxers were found to have increased active and passive external rotation as well as a significantly higher degree of scapular dyskinesia compared to the control group. This kinetic profile could produce a higher risk of chronic and acute shoulder and upper extremity injury in the boxing group owing to altered biomechanics.

1.6 Disability from upper extremity injury

1.6.1 Impairment and disability rating of upper extremity injury

The level of impairment, referring to physiological loss of function resulting from hand injury, may be seen as small given the relative size of the injury. However, grip strength has been demonstrated to be significantly lower in boxers that have sustained an injury to the hand and/or wrist.(47) This is in contrast to disability, which refers to the inability of a person to perform tasks necessary for their daily function and activities and is highly dependent on handedness, career and other personal factors. Measured disability secondary to upper extremity injury is well documented in the workers compensation board literature, and can significantly affect work ability, activities of daily living, and overall function. Disability ratings for hand loss-of-function are rated as high as 70% for the dominant hand and 60% for the non-dominant hand, representing a significant detriment to functional capacity.(48)

1.6.2 Cost associated with upper extremity injury in the combat sport athlete

The overall cost of hand dysfunction and disability is difficult to calculate, as it is highly dependent on handedness as well as respective job and career requirements. A comparison of closed non-operative versus operative management of boxer's fractures demonstrated an overall cost increase of 1100 euros (equivalent to $1692.09 Canadian dollars at a conversion rate of 1 euro = 1.54 Canadian dollars (49)) if surgical management was performed.(50) The ability to apply force through an injured hand or finger after injury is dependent on the location and type of injury, but is typically delayed for 6 to 12 weeks post-injury. Many professional athletes are self-employed, are involved in training other athletes or receive sponsorship as a means of income. The inability to either train or participate in matches secondary to hand/wrist injury or disability could therefore result in significant costs to the athlete due to a direct loss of income.

1.7 Prevention of upper extremity injury in combat athletes

1.7.1 Protective equipment in combat athletes

Various designs of protective training equipment are available for the head, mouth, forearms, hands, groin, shins and feet, making it difficult for athletes to navigate and choose the most appropriate and cost-effective options. Mouthguards directly protect the teeth in contact sports and help absorb and dissipate energy from direct blows to the head in the prevention of brain injury. Studies have clearly demonstrated that the overall stiffness of mouthguards is the most important factor in the prevention of dental injury.(51) Despite this knowledge, most available mouthguards are made out of low stiffness materials, and therefore provide minimal protection against injury to the tooth-bone interface. This clouds the ability of athletes to choose the most appropriate protection against oral trauma, as the availability of high stiffness mouthguards is minimal, or is only available at a much higher price point.

Despite the potential for injury, it has clearly been shown that the use of protective hand equipment is associated with decreased burden of injury. The use of hand protection decreases the proportion of hand injuries in karate athletes from 11% to 1.3% and decreases the overall number of injuries requiring treatment from 42% to 16%, including those injuries incurred by the opponent.(22) Hand and wrist injury has the potential for significant disability, however, most combat-related musculoskeletal research to date has focused on either categorizing athletic injuries incurred by a given sport or furthering the potential damage that an athlete can inflict on an opponent.(21, 22, 52-56) Therefore, although traditional protective gear is often used in a variety of combat sport practices, there is a paucity of research investigating the effectiveness of protective hand gear for the practitioner.

1.7.2 Traditional and modern hand wraps used by combat athletes

The traditional hand protection used in multiple striking sports includes material (i.e., cotton, rope, gauze) wrapped around the hand, wrist and fingers. The most common form is a 4 centimeter (cm) by 457.2 cm (180 inch) long cotton-polyester linear wrap. This style of wrap is anchored at the thumb and successively wrapped around the wrist and metacarpals, in between the index through small digits in the interphalangeal spaces and finally secured back around the hand and wrist (Figure 1.4). In theory, these wraps have the potential to provide direct impact absorption as they do overlie the MCP joints and proximal phalanges. Rather, they are more likely to provide stability to the hand by tensioning the deep transverse metacarpal ligaments and by preventing excessive carpal/wrist flexion, extension and radioulnar deviation. There is, however, no literature available that has investigated how these wraps function to protect the hands. Rather, the only study to date investigating boxing hand wraps directly looked at the stiffness and force generation of the professional boxing wrap construct, consisting of gauze and diachylon.(57) In this study of 22 professional boxers, the authors found that increased thickness of the wrap resulted in increased overall stiffness of the hand as well as an increased force generation as measured by an impact sensor. While this is important information on the performance of athletes during a match, this does not inform athletes on how to best protect their own hands during matches or in training where the gauze/diachylon wraps are not routinely used.

Figure 1.4. Demonstration of a version of a hand-wrap technique using the 180 inch (457.2 cm) linear wraps. A. The thumb loop is anchored at the base of the thumb and wrapped

around the wrist joint. B. The wrap is then carried up to the metacarpals and proximal phalanges. C. The wrap is successively wrapped through the fourth, third and second web spaces and base of the thumb. D. The wrap is secured around the MCP joints. E. The wrap is criss-crossed around the dorsum of the wrist. F. The wrap is finally wrapped and secured around the wrist joint.

Modern styles of wraps have attempted to integrate foam or solid gel into the wrap that directly overlies the MCP joints. A biomechanical analysis of foam-based foot and forearm guards used in Taekwondo was performed to investigate whether this combination of protection, which mimics a simultaneous head kick and forearm block, significantly decreased the transmitted force. The authors demonstrated that the combination of guards were able to absorb 15.9% of the applied force and distributed the force across a wider area.(58) An alternate study looked at the ability of a variety of hand, forearm, foot and shin guards from commercially available brands to absorb impact from a vertically dropped weight.(59) The weight was dropped from heights to mimic an impact force of 8-15 Joules, which corresponds to the amount of energy required to cause a ligamentous rupture or fracture. The hand protectors tested were unable to dissipate the transmitted energy below this critical level, implying that the hand protectors were incapable of preventing injury. However, as the analysis used in both studies uses an artificial setting, it does not truly represent the forces generated in a clinical dynamic training scenario.

1.8 Force measurements of striking in combat athletes

1.8.1 Force and impact sensors used in combat sport training

Force sensors have been used in a wide variety of medical applications and have provided significant insight into ergonomic designs for handles, workstations and even athletic footwear. In-shoe pressure and force distribution sensors have also been used effectively to determine plantar pressure points in diabetic feet, allowing progressive designs in footwear to accommodate and prevent advancement of foot ulcers.(60) These types of sensors allow for innovative designs in multiple fields, which both help to prevent injury and enhance athletic performance. In the field of combat sports, force sensors are often used in training to measure the forward force and potential damage that an athlete can inflict on an opponent. This technique has been used to estimate the differences in force in various types of protective gear as outlined in previous sections.(57-59) Straight punches, elbows and open hand strikes performed by professional or advanced self-defence adults during kneeling attacks were similarly measured using force plate sensors to determine the maximum amount of force that could be generated.(61)

1.8.2 Accelerometers and gyroscopes used in combat sport training

Accelerometers and gyroscopes are instruments which have been applied to boxers in order to measure position, velocity, acceleration and, indirectly, forward force measurements.(62-64) There are now a wide variety of commercially available accelerometers used for combat sports with Bluetooth capabilities. The accelerometers can easily be attached at the wrist when applied and held under hand wraps or in pre-fabricated bracelets. The use of accelerometers and gyroscopes have been clinically validated and are feasible for use in combat sport training as well as for research purposes.(63, 65)

1.8.3 Principles of force and impact measurement

Several previous studies have investigated the amount of forward force that is generated during closed hand strikes in combat athletes.(61, 66) These studies demonstrated upwards of 4000 Newtons of forward force based on laboratory analyses. A study performed with force sensors within boxing gloves during a professionally sanctioned match found significantly lower values, with a maximum mean measurement of 1600 Newtons (N) in one athlete.(67) To the best of our knowledge, there are no studies looking at the level of force at the interface between the protective hand wraps and the MCP joints and proximal phalanges of the athlete, where the retrograde force could cause potential hand and wrist injury during striking.

The Nyquist theorem is a principle of data acquisition that can be applied to force and impact measurements. This theorem states that to accurately capture a sinusoidal signal, the sampling rate must be twice the rate of the measured signal. Most studies to date have analyzed "touch time", i.e., time from stimulus to time of contact, rather than total contact time of hand to sensor or bag. Touch time measurements have been measured between 432 to 750 milliseconds.(68) Extrapolation of graphically represented punch force curves from this study demonstrates a total contact measurement time of approximately 25 milliseconds. Closed fist strikes have otherwise been demonstrated to have a mean impact time of 26 milliseconds, which is equivalent to approximately 50 Hertz (Hz).(45) Therefore, a minimum 100 Hz capture rate should be sufficient to capture impact and force measurements in a striking study.

1.9 Goals of this thesis

1.9.1 Aims

Based on the potential for upper extremity injury and disability, analyzing the protective capabilities of protective hand gear in a clinical setting would benefit combat sport athletes and allow evidence-based recommendations for the most effective protective equipment. Protective hand wraps that provide increased impact absorption at the surface of the hand could potentially provide the greatest benefit for injury prevention in this athletic group. This study aims to address the knowledge gap by quantifying the efficacy of hand wraps from a self-protective standpoint, by measuring the level of force that is transmitted to the surface of the hand during striking using two commonly used types of hand wrap protection including a traditional style wrap as well as one including gel-reinforcement.

1.9.2 Hypothesis

We hypothesize that gel-reinforced hand wraps will provide improved force dissipation and decreased force transmission to the MCP joints and wrist compared to the traditional "intermetacarpal" style of wrap using linear hand wraps.

1.9.3 Outcomes

The primary outcome measure will include the calculated mean force from sustained peak readings from a series of punches thrown with either the gel-reinforced or linear hand wraps. Subgroups will be used to trend force measurement differences based on experience level, sex, and relative weight divisions. Secondary outcomes will include athlete preference and subjective performance of the two types of hand wraps.

Chapter 2. Systematic review of the literature

Eva M. Gusnowski, Manisha R. Mistry, Daniel Langohr, Kenneth Faber and Ruby Grewal

2.1 Introduction

To properly understand the level of intervention for injury prevention, it is important to categorize the type and location of injury sustained by an athletic population. Of interest to this thesis is the categorization of hand and wrist injury in combat athletes, which has not been previously or adequately addressed. Herein is described an extensive systematic review to characterize the location and type of injury sustained by combat athletes from a wide variety of sports, experience levels, training scenarios and mechanism of combat.

2.2 Materials and methods

A systematic review of the literature was performed following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines to identify hand and wrist injuries incurred during combat sport training or matches.(69) The search was performed using two electronic databases, PubMed and Web of Science, on January 9, 2021 (Figure 2.1). The search terms used included (“combat sports” OR “martial arts” OR “boxing” OR “jiu jitsu” OR “karate” OR “taekwondo” OR “mixed martial arts” OR “MMA” OR “kickboxing” OR “kung fu” OR “aikido” OR “muay thai” OR “krav maga” OR “tai chi” OR “capoeira” OR “judo”) AND (“hand” OR “wrist” OR “finger” OR “metacarpal” OR “carpus” OR “forearm” OR “upper extremity” OR “bone” OR “joint” OR “tendon” OR “soft tissue” OR “ligament”) AND (“injury” OR “trauma” OR “damage” OR “fracture” OR “dislocation” OR “subluxation” OR “rupture”). The date range was inclusive from inception to January 9, 2021.

Full-text studies were included if: 1) a hand/wrist injury occurred during combat training or competition; 2) an adequate breakdown of location to individual bone, joint or soft tissue structure was provided; 3) an adequate breakdown of injury subtype was provided (i.e., fracture, strain, sprain, dislocation, tendon rupture); and 4) original data from a peer reviewed article was provided. The “hand/wrist” was defined as the anatomical area extending from 5 cm proximal to the distal radioulnar joint and any structure distal. Studies were excluded if they met the following criteria: 1) non-English; 2) conference abstracts; 3) no full text available online or in print for review; or 4) studies that did not meet inclusion criteria. Initial abstract/title screening was performed by one reviewer (E.M.G). Full-text articles identified for potential inclusion were reviewed by two independent reviewers (E.M.G. and M.R.M.). Disagreements were resolved by consensus among the investigators.

Categorization of the injuries was based on a variety of factors related to general combat sports. Sport fields included boxing, karate, judo, kickboxing, Muay Thai, jiu jitsu, krav maga, mixed martial arts and taekwondo. Experience level was defined as either elite/professional (including Olympians, national-level athletes and those with sanctioned professional matches or licensure), amateurs/recreational, military/police, pediatric (less than 18 years of age) or undefined. Sports were differentiated based on their mechanism of combat, categorized as striking only (boxing), throws only (judo and jiu jitsu) or a combination of both strikes and throws (karate, kickboxing, Muay Thai, krav maga, mixed martial arts and taekwondo). Injury acuity was included as either acute injury (defined as those recorded within 3 months of initial injury), chronic injury (defined as those recorded >3 months of initial injury), acute on chronic (defined as a repeat injury in the setting of a previous known injury and recorded within 3 months of repeat injury) or undefined. Timing of injury was defined as those occurring during a match or tournament, during training or unknown.

2.3 Results

2.3.1 Study characteristics

The initial database search yielded 2898 studies; 398 duplicates were excluded. A total of 2500 studies were screened for inclusion (Figure 2.1). After primary abstract and title review, 2261 articles were excluded and 3 articles could not be retrieved online or in print through available library services, leaving 236 articles for application of inclusion/exclusion criteria as described above. Overall, 40 articles met final inclusion/exclusion criteria after secondary screening between the two investigators (Table 2.1). The included papers spanned multiple decades, ranging from 1970 to 2020, with the majority (n = 27, 67.5%) published since 2000.

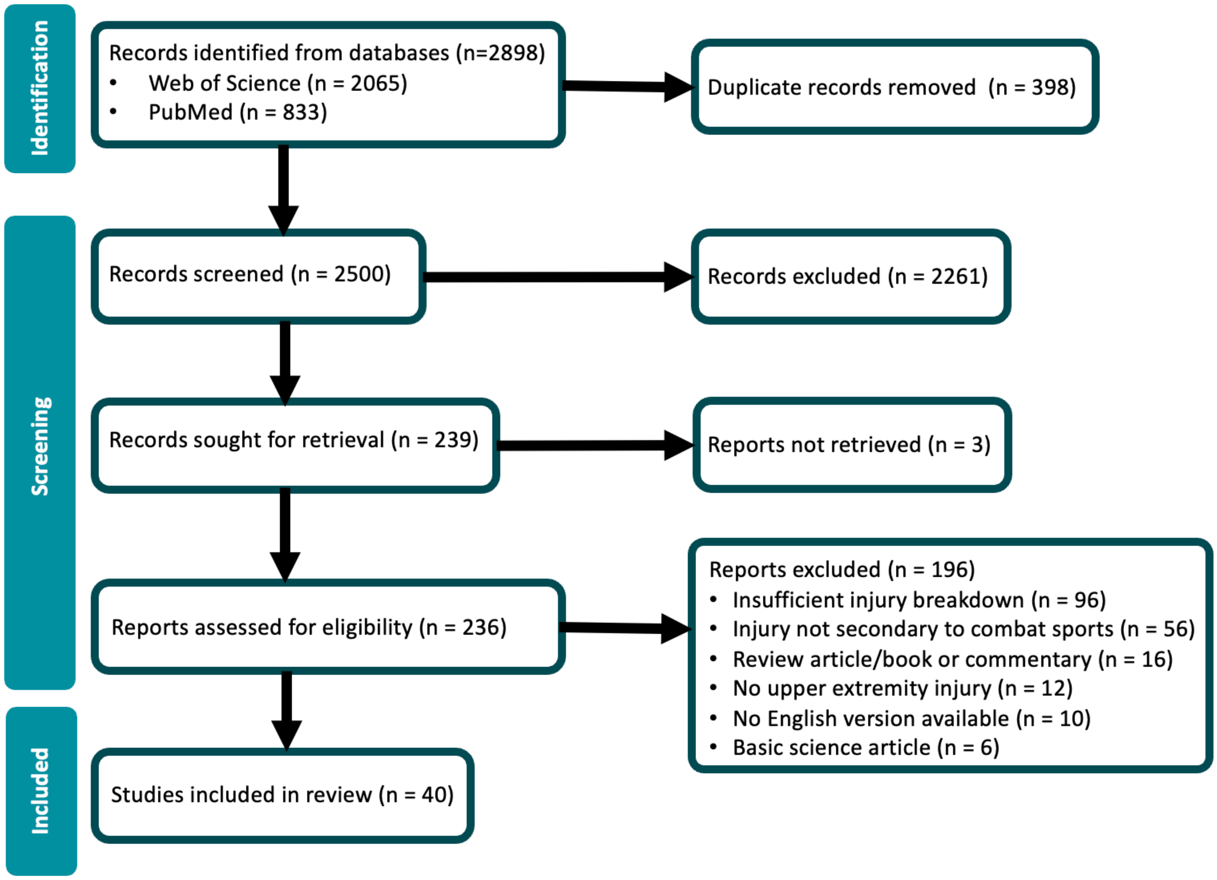

Figure 2.1. Modified PRISMA flow diagram for systematic review of hand and wrist injuries in combat athletes.

The highest representation of sport was in the field of boxing (n = 17/40, 42.5%). This was followed in descending order by karate (n = 11/40, 27.5%), judo (n = 4/40, 10%), mixed martial arts (n = 3/40, 7.5%) and taekwondo (n = 2/40, 5%). The remaining sports, including kickboxing, Muay Thai, jiu jitsu and krav maga each had a single study that met inclusion criteria (n = 1/40 per sport, 2.5%). Involvement of the total number of athletes screened to determine incidence of injury in each field of sport could not be adequately determined, as most included studies involved case reports and case series and/or these numbers were not reported to allow accurate calculations.

Title	Lead author	Year	Journal	Study	Sport	Sport Type	Chronicity	Experience	Training	Summary of injuries
Hypertrophic Infiltrative Tendinitis (HIT Syndrome) of the Long Extensor: The Abused Karate Hand (70)	Gardner	1970	JAMA	Case report	Karate	Combination	Chronic	Military	Training	Middle finger extensor hypertrophy and adhesions over MCP (n = 1)
Boxing Safety and Injuries (71)	McCown	1979	Phys Sportsmed	Retrospective cohort chart review	Boxing	Striking	Unclear	Professional	Unknown	Finger phalanx fracture (n = 8); finger MC fracture (n = 15)
Index Metacarpal Fractures in Karate (72)	Kelly	1980	Phys Sportsmed	Cross sectional cohort case series	Karate	Combination	Unclear	Amateur/ recreational	Unknown	Thumb MC fracture (n = 3); finger MC fracture (n = 8)
Ununited fractures of the scaphoid in boxers: A therapeutic dilemma (73)	Shively	1980	Am J Sports Med	Case report	Boxing	Striking	Chronic and acute on chronic	Elite	Unknown	Scaphoid non-union (n = 3); index MCP chronic pain/swelling (n = 1)
Does karate injure blood vessels of the hand? (74)	Vayssairat	1984	The Lancet	Case report	Karate	Combination	Chronic	Elite	Unknown	Digital artery occlusion/aneurysm with digital ulcers (n = 1)
Boxer's knuckle--dorsal capsular rupture of the metacarpophalangeal joint of a finger (75)	Posner	1989	J Hand Surg (Am Vol)	Observational	Boxing	Striking	Chronic	Professional and amateur	Unknown	Extensor hood rupture (professional/elite (n = 4); amateur (n = 2))

Table 2.1. Characteristics of included studies in the performed systematic review (continued on the following 6 pages). (Abbreviations used: MCP, metacarpophalangeal; MC, metacarpal; DRUJ, distal radioulnar joint; UCL, ulnar collateral ligament; ECRL/B, extensor carpi radialis longus/brevis; RC, radiocarpal; EDC, extensor digitorum communis; EPL, extensor pollicis longus; EDM, extensor digit minimi; FDP, flexor digitorum profundus; DIP, distal interphalangeal; PIP, proximal interphalangeal; CMC, carpometacarpal; EPB, extensor pollicis brevis; AVN, avascular necrosis; SH2, Salter Harris 2; FCR, flexor carpi radialis).

Title	Lead author	Year	Journal	Study	Sport	Sport Type	Chronicity	Experience	Training	Summary of injuries
Dorsal dislocation of the distal end of the ulna in a judo player (76)	Russo	1991	Acta Orthop Belg	Case report	Judo	Throws	Acute	Police	Training	Dorsal DRUJ dislocation (n = 1)
The true 'boxer's fracture? (77)	Cavanagh	1992	Injury	Case report	Boxing	Striking	Acute	Professional	Match	Trapezium fracture (n = 1)
"Karate Kid" Finger (78)	Chiu	1993	Plast Reconstr Surg	Case report	Karate	Combination	Chronic	Pediatric	Training	Segmental perineural and interfascicular fibrosis of dorsal branch of ulnar digital nerve (n = 1)
Hypothenar hammer syndrome in sports (79)	Miller	1996	Knee Surg Sports Traumatol Arthrosc	Case series	Karate	Combination	Unclear	Unknown	Unknown	Hypothenar hammer syndrome (n = 1)
Incidence and Severity of Injuries Resulting From Amateur Boxing in Ireland (80)	Porter	1996	Clin J Sports Med	Prospective cohort	Boxing	Striking	Acute	Amateur	Match	Thumb UCL injury (n = 2); ECRL/B partial tear (n = 1); RC joint strain (n = 1); extensor hood rupture (n = 1); EDC tendon partial tear (n = 1); MC fracture (n = 2); trapezium fracture (n = 1)
Spontaneous rupture of extensor pollicis longus tendon in a kick boxer (81)	Lloyd	1998	Br J Sports Med	Case report	Kick-boxing	Combination	Acute	Elite	Training	EPL rupture (n = 1)
Knuckle pads from boxing (82)	Kanerva	1998	Eur J Dermatol	Case report	Boxing	Striking	Chronic	Recreation-al	Unknown	Hyperkeratosis/fis-sured callosities at DIP of index and middle fingers (n = 1)
Boxer's Knuckle: Traumatic Disruption of the Extensor Hood (83)	Hame	2000	Hand Clinics	Case report	Boxing	Striking	Unclear	Professional	Unknown	Extensor hood rupture (n = 27)

Table 2.1 continued.

Title	Lead author	Year	Journal	Study	Sport	Sport Type	Chronicity	Experience	Training	Summary of injuries
Injury and injury rates in Muay Thai kick boxing (84)	Gartland	2001	Br J Sports Med	Cross sectional survey	Muay Thai	Combination	Acute	Unknown	Unknown	Finger phalanx fracture (n = 9); finger MC fracture (n = 10); thumb hyperextension injury (n = 6); carpal fracture (n = 9); wrist strain n = (10)
Karate Cicatrices (85)	Adams	2001	Cutis	Case report	Karate	Combination	Chronic	Unknown	Unknown	Scars on back of hands (n = 1)
Treatment of soft tissue injuries to the dorsum of the metacarpophalangeal joint (Boxer's knuckle) (86)	Arai	2002	J Hand Surg Eur Vol	Retrospective cohort	Boxing and karate	Striking (boxing) and combination (karate)	Acute	Professional and recreational	Unknown	Extensor hood rupture (boxing (n = 3); karate (n = 2))
Traumatic extensor tendon dislocation in a boxer: a case study (87)	Bents	2003	Med Sci Sports Exerc	Case report	Boxing	Striking	Chronic	Elite	Unknown	Little EDC and EDM longitudinal split (n = 1); ulnar capsular rupture (n = 1)
Extensor retinaculum graft for chronic boxer's knuckle (88)	Nagaoka	2006	J Hand Surg (Am Vol)	Case series	Boxing	Striking	Chronic	Professional	Unknown	Extensor hood rupture (n = 5)
Long-term follow-up of hypothenar hammer syndrome: a series of 47 patients (89)	Marie	2007	Medicine (Baltimore)	Case series	Karate	Combination	Chronic	Professional	Unknown	Hypothenar hammer syndrome (n = 1)
Disabling hand injuries in boxing: boxer's knuckle and traumatic carpal boss (90)	Melone	2009	Clin J Sports Med	Case series/ technique	Boxing	Striking	Chronic	Professional	Unknown	Extensor hood rupture (n = 44); symptomatic carpal boss (n = 38)
Small flake, big problem: an unreported cause of extensor pollicis longus tendon rupture (91)	Durrant	2010	Ann R Coll Surg Engl	Case report	Martial arts	Combination	Acute	Unknown	Unknown	ECRL avulsion fracture at base of third MC with EPL rupture (n = 1)

Table 2.1 continued.

Title	Lead author	Year	Journal	Study	Sport	Sport Type	Chronicity	Experience	Training	Summary of injuries
A rare presentation of flexor digitorum profundus type V avulsion injury with associated intra-articular fracture: A case report (92)	Rizis	2011	Plast Surg	Case report	Karate	Combination	Acute	Unknown	Training	Bony FDP avulsion (type V) of ring finger (n = 1)
Simultaneous triple dislocation of the small finger (93)	Vidal	2013	J Hand Surg (Am Vol)	Case report	Karate	Combination	Acute	Unknown	Unknown	Small finger simultaneous DIP/PIP/MCP dislocation (n = 1)
Acute isolated volar dislocation of the distal radio-ulnar joint: case report and literature review (94)	Werthel	2014	Chir Main	Case report	Martial arts	Combination	Acute	Unknown	Unknown	Volar DRUJ dislocation (n = 1)
Assessment of Injuries During Brazilian Jiu-Jitsu Competition (95)	Scoggin	2014	Orthop J Sports Med	Descriptive epidemiol-ogical	Jiu jitsu	Throws	Acute	Amateur	Tournam-ent	Finger DIP strain (n = 1), thumb sprain (n = 1), index finger PIP dislocation (n = 1), ring finger MC fracture (n = 1)
Combined joint fusion for index and middle carpometacarpal instability in elite boxers (96)	Nazarian	2014	J Hand Surg Eur Vol	Case series	Boxing	Striking	Chronic	Elite	Unknown	Index and middle finger CMC instability (n = 13)
Injuries in competitive boxing. A prospective study (97)	Siewe	2015	Int J Sports Med	Prospective cohort	Boxing	Striking	Acute	Professional	Unknown	Finger MCP fracture (n = 1); finger interphalangeal joint capsule injury (n = 2); finger MCP bruise (n = 3); wrist contusion (n = 23); hand laceration/contusion n = 1

Table 2.1 continued.

Title	Lead author	Year	Journal	Study	Sport	Sport Type	Chronicity	Experience	Training	Summary of injuries
Stress Fracture of the Radial Styloid Process in a Judo Player: A Case Report (98)	Hashiguc-hi	2015	J Nippon Med Sch	Case report	Judo	Throws	Acute on chronic	Pediatric	Training	Radial styloid stress fracture (n = 1)
Ultrasound imaging for the extensor pollicis brevis tendon: when martial arts caused partial rupture (99)	Chang	2015	Am J Phys Med Rehabil	Case report	Martial arts	Combination	Acute	Unknown	Unknown	EPB partial rupture (n = 1)
Florid reactive periostitis in the fifth phalange of a professional boxer: A case report (100)	Tomori	2016	Medicine (Baltimore)	Case report	Boxing	Striking	Chronic	Professional	Unknown	Reactive periostitis of left small finger proximal phalanx and MC (n = 1)
The Role of Dynamic Contrast-Enhanced MRI in a Child with Sport-Induced Avascular Necrosis of the Scaphoid: A Case Report and Literature Review (101)	Koc	2016	Case Rep Orthop	Case report	Karate	Combination	Chronic	Pediatric	Unknown	Scaphoid AVN (n = 1)
Extensor Tendon Instability Due to Sagittal Band Injury in a Martial Arts Athlete: A Case Report (102)	Kochevar	2017	J Hand Surg Asian Pac	Case report	Tae-kwondo	Combination	Chronic	Pediatric	Unknown	Extensor hood rupture (n = 1)
Hook Plate Fixation for the Thumb Ulnar Collateral Ligament Fracture-Avulsion (103)	Tabrizi	2017	J Hand Microsurg	Case report	Tae-kwondo	Combination	Acute	Amateur	Tournam-ent	Thumb UCL avulsion (n = 1)

Table 2.1 continued.

Title	Lead author	Year	Journal	Study	Sport	Sport Type	Chronicity	Experience	Training	Summary of injuries
Prevalence and Patterns of Injury Sustained During Military Hand-to-Hand Combat Training (Krav-Maga) (28)	Farkash	2017	Mil Med	Retrospect-ive cohort chart review	Krav maga	Combination	Acute	Military	Training	Finger phalanx fracture (n = 10); finger interphalangeal joint dislocation (n = 1); finger MC fracture (n = 7); jersey finger (n = 1); finger contusion (n = 35); thumb phalanx fracture (n = 7); thumb MC fracture (n = 2); thumb collateral ligament tear (n = 4); thumb contusion (n = 83); scaphoid fracture (n = 12); triquetrum fracture (n = 2); trapezoid fracture (n = 1); distal radius fracture (n = 1); ulnar styloid fracture (n = 2); hand or wrist sprain/strain/contusio n (n = 107); hand or wrist laceration (n = 3)
Closed disruption of a single flexor digitorum superficialis tendon slip: 3 cases (104)	Schweizer	2019	Hand Surg Rehabil	Case series	Judo	Throws	Acute	Unknown	Unknown	Disruption of right middle finger radial slip of FDS (n = 1)
Index extensor digitorum communis tendon entrapment in a growth plate injury of distal radius (105)	Furuya	2019	Trauma Case Rep	Case report	Judo	Throws	Acute	Pediatric	Unknown	Distal radius SH2 fracture with index EDC tendon entrapment/rupture (n = 1)

Table 2.1 continued.

Title	Lead author	Year	Journal	Study	Sport	Sport Type	Chronicity	Experience	Training	Summary of injuries
Isolated Trapezoid Fracture in a Boxer (106)	Ribeiro	2019	Am J Case Rep	Case report	Boxing	Striking	Acute	Recreation-al	Training	Trapezoid fracture (n = 1)
Surgical Repair of an Avulsed Distal Flexor Carpi Radialis Tendon in a Boxer: A Case Report (107)	Berthiau-me	2019	JBJS Case Connect	Case report	Boxing	Striking	Acute	Professional	Unknown	FCR avulsion (n = 10: finger MC fracture (n = 1)
Dorsal Dislocation of the Trapezoid with Metacarpal Instability: A Boxing Injury (108)	Feder	2020	J Wrist Surg	Case report	Boxing	Striking	Acute	Professional	Match	Scaphotrapeziotrape-zoidal joint dislocation and index/middle CMC dislocations (n = 1)

Table 2.1 continued.

2.3.2 Basic injury breakdown

Each paper was categorized based on sport, experience (professional/elite, amateur/recreational, military/police, pediatric or unknown), sport subtype (striking only, throws only or combination), injury acuity (acute, chronic, acute on chronic or unknown) and timing of injury (match/tournament, training or unknown). Injuries were initially broadly categorized as fracture, joint injury, contusion or sprain, soft tissue injury, neurovascular, or chronic bone or joint injury. The basic injury breakdown for each of the categories are shown in Table 2.2 through Table 2.6.

	SPORT								
	Boxing	Karate	Judo	Kickboxing	Muay Thai	Jiu jitsu	Krav maga	Mixed Martial Arts	Taekwondo
Fracture	30	11	1	0	28	1	44	0	0
Joint injury	18	1	1	0	0	1	5	1	1
Contusion or Sprain	28	0	0	0	16	2	225	0	0
Soft tissue injury	93	4	1	1	0	0	4	3	1
Neurovascular	0	3	0	0	0	0	0	0	0
Chronic bone or joint injury	17	3	1	0	0	0	0	0	0
TOTAL	186	22	4	1	44	4	278	4	2

Table 2.2. Hand and wrist injury category breakdown based on sport subtype.

Table 2.2 shows the basic injury breakdown based on individual sport. The two combat disciplines with the highest number of upper extremity injuries are boxing (n = 186) and krav maga (n = 278). Kickboxing, judo, jiu jitsu, mixed martial arts and taekwondo all had less than 5 upper extremity injuries in the included studies. The largest number of reported injuries in boxing was in the soft tissue category (n = 93/186, 50.0%), whereas the largest number of reported injuries in krav maga was in the contusion/abrasion category (n = 225/278, 80.9%).

	EXPERIENCE				
	Elite or professional	Amateur or recreational	Military or Police	Pediatric (<18 years of age)	Unknown
Fracture	26	16	44	1	28
Joint injury	16	4	6	0	2
Contusion or Sprain	27	3	225	0	16
Soft tissue injury	87	9	5	1	5
Neurovascular	2	0	0	0	1
Chronic bone or joint injury	16	1	0	3	1
TOTAL	**174**	**33**	**280**	**5**	**53**

Table 2.3. Hand and wrist injury category breakdown based on experience level.

Table 2.3 above demonstrates the generalized breakdown of hand and wrist injuries based on athlete experience level. The highest number of injuries were incurred in military or police training (n = 280/545, 51.4%) and elite or professional athletes (n = 174/545, 31.9%). Elite or professional athletes had a high proportion of soft tissue injury (n = 87/174, 50.0%) whereas military or police sustained a high proportion of contusions/sprains (n = 225/280, 80.3%).

	SPORT TYPE		
	Striking only	Throws only	Striking and throws
Fracture	30	2	83
Joint injury	18	2	8
Contusion or Sprain	28	2	241
Soft tissue injury	94	2	11
Neurovascular	0	0	3
Chronic bone or joint injury	17	1	3
TOTAL	**187**	**9**	**349**

Table 2.4. Hand and wrist injury category breakdown based on mechanism of combat.

Table 2.4 shows the generalized breakdown of injuries based on sport type. The highest number of hand and wrist injuries were incurred in the practice of combat sports that employed both striking and throws (n = 349/545, 64.0%), followed by those that employ striking only (n = 187/545, 34.3%).

	INJURY ACUITY			
	Acute	**Chronic**	**Acute on chronic**	**Unknown**
Fracture	92	0	0	23
Joint injury	15	13	0	0
Contusion or Sprain	271	0	0	0
Soft tissue injury	18	62	0	27
Neurovascular	0	2	0	1
Chronic bone or joint injury	0	19	2	0
TOTAL	**396**	**96**	**2**	**51**

Table 2.5. Hand and wrist injury category breakdown based on injury acuity.

	TRAINING		
	Match or competition	**Training**	**Unknown**
Fracture	5	45	65
Joint injury	7	6	15
Contusion or Sprain	3	225	43
Soft tissue injury	3	7	97
Neurovascular	0	0	3
Chronic bone or joint injury	0	2	19
TOTAL	**18**	**285**	**242**

Table 2.6. Hand and wrist injury category breakdown based on timing of injury during competition or training.

Most injuries occurred in the acute setting (Table 2.5), with a slight majority occurring during training (n = 285/545, 52.3%) versus those with no clear report of incident during training versus competition (n = 242/545, 44.4%). The fewest amount of hand and wrist injuries occurred during matches or competition (n = 18/545, 3.3%; Table 2.6).

2.3.3 Detailed injury breakdown

Tables A2.1 through A2.6 (see Appendix A) demonstrate a detailed injury breakdown based on sport subtype. The highest number of fractures (Table A2.1) occurred in the finger phalanges and finger metacarpals in boxing (finger phalanx n = 8/30, 26.7%; finger metacarpal n = 19/30, 63.3%) and Muay Thai (finger phalanx n = 9/28, 32.1%; finger metacarpal n = 10/28, 35.7%). A high number of finger phalanx and finger metacarpal fractures were also noted in krav maga (finger phalanx n = 10/44, 22.7%; finger metacarpal n = 7/44, 15.9%). Out of the included combat sports, krav maga practitioners incurred the highest proportion of thumb phalanx and metacarpal fractures (n = 9/44, 20.5%) and carpal fractures (n = 15/44, 34.0%). The highest proportion of joint injuries occurred in boxing (Table A2.2, n = 18/28, 64.3%), located most commonly at the finger CMC joints (n = 15/18, 83.3%). Krav maga athletes incurred the highest number of contusions and sprain hand and wrist injuries (Table A2.3, n = 225/271, 83.0%), followed by boxing (n = 28/271, 10.3%) and Muay Thai (n = 16/271, 5.9%). The highest proportion of soft tissue injuries (Table A2.4) was in boxing, representing 86.7% (n = 93/107) of the total number of soft tissue injuries. Most of the boxing soft tissue injuries were extensor hood ruptures (n = 86/93, 92.5%). Very few neurovascular injuries were noted, with a total of only 3 injuries (3/545, 0.6%), all of which were found in karate athletes (Table A2.5). Chronic repetitive impact injuries were most common in boxers (Table A2.6, n = 17/21, 81.0%).

Tables A2.7 through A2.12 demonstrate the detailed injury breakdown based on the experience level of participants. Military/police had the highest proportion of fractures altogether (n = 44/115, 38.2%; Table A2.7), followed by elite/professional athletes (n = 26/115, 22.6%) and amateur/recreational athletes (n = 16/115, 13.9%). Of note, elite/professional athletes had the highest number of fractures in the finger metacarpals (n = 17/26, 65.4%). Elite/professional athletes experienced the highest number of reported joint injuries (n = 16/22, 72.7%), with the highest representation in the finger CMC joints (n = 15/16, 93.8%; Table A2.8). Table A2.9 shows that the highest proportion of contusions/sprains was found in the military/police subcategory (n = 225/271, 83.0%), followed by elite/professionals (n = 27/271, 10.0%). The highest proportion of soft tissue injuries were also found in elite/professional athletes (n = 87/107, 81.3%; Table A2.10), wherein most of these injuries were extensor hood ruptures (n = 81/87, 93.1%). Neurovascular injuries (Table A2.11) were only found in the elite/professional (n = 2/3, 66.7%) and unknown categories (n = 1/3, 33.3%), whereas chronic injuries (Table A2.12) were most commonly reported in the elite/professional (n = 16/21, 76.2%) and pediatric (n = 3/21, 14.3%) categories. Pediatric athletes had the fewest number of hand and wrist injuries reported in all injury subcategories (Tables A2.7 through 2.12).

Tables A2.13 through A2.18 report the detailed injury breakdown based on mechanism of combat. Combat sports that employed striking only or a combination of striking and throws consistently represented a higher proportion of overall injury subtypes compared to those that employed only throws. Combat athletes performing sports that employed both striking and throws had the highest proportion of total hand and wrist fractures (n = 83/115, 72.2%; Table A2.13), with the highest proportion of fractures reported at the finger metacarpals (n = 25/83, 30.1%). In combat sports that employ only striking, the highest proportion of fractures were also found in the finger metacarpals (n = 19/30, 63.3%; Table A2.13), and the highest proportion of joint injuries were reported at the finger CMC joints (n = 15/18, 83.3%; Table A2.14). The highest proportion of contusions/sprains were reported in striking/throw combination sports (n = 241/271, 88.9%; Table A2.15), with the second highest in striking only sports (n = 28/271, 10.3%). Soft tissue injuries were most common in striking only sports (n = 94/107, 87.9%; Table A2.16), with the highest proportion of injury in the extensor hood rupture category (n = 86/94, 91.5%). Neurovascular injuries were only reported in the combined striking/throw sports (n = 3/3, 100%; Table A2.17), whereas striking only sports had the highest proportion of chronic injuries (n = 17/21, 81.0%; Table A2.18). Sports that employ only throws had the lowest proportion of injury in all categories.

Tables A2.19 through A2.24 contain a breakdown of hand and wrist injury based on acuity of reported injury. Acute injuries (i.e., those reported within 3 months of injury) constituted the highest proportion of fractures (n = 92/105, 87.6%; Table A2.19), joint injuries (n = 15/28, 53.6%; Table A2.20) and contusions/sprains (n = 271/271, 100%; Table A2.21). Chronic injuries (i.e., those reported more than three months after injury) constituted the highest proportion of soft tissue injuries (n = 62/107, 57.9%; Table A2.22), neurovascular (n = 2/3, 66.7%; Table A2.23) and long-term injuries (n = 19/21, 90.5%; Table A2.24). Acute on chronic injuries were only found in the long-term chronic injury category (n = 2/21, 9.5%; Table A2.24).

Tables A2.25 through A2.30 contain the detailed injury breakdown of hand and wrist injury sustained during matches/tournaments versus training. Training resulted in 42.9% of the reported fractures (n = 45/105; Table A2.25), compared to matches/tournaments which resulted in 4.8% (n = 5/105) and unknown timing of injury in 61.2% (n = 65/105). Joint injuries were slightly more common in matches/tournaments at 25% (n = 7/28; Table A2.26) compared to training (n = 6/28; 21.4%). A high proportion of contusions/sprains (n = 225/271, 83.3%; Table A2.27) occurred during training. Most of the soft tissue injuries did not report the timing of injury (n = 97/107, 90.7%; Table A2.28), with training accounting for 6.5% (n = 7/107) of reported injuries and matches/tournaments accounting for 2.8% (n = 3/107). The highest proportion of joint injuries (n = 15/28, 53.6%; Table A2.26), all of the neurovascular injuries (n = 3/3, 100%; Table A2.29) and most of the chronic injuries (n = 19/21, 90.5%; Table A2.30) did not report timing of injury.

2.4 Discussion

The distribution and categorization of injury in sport is an integral step in determining what measures can be taken to mitigate injury. If trauma is considered as a disease, injury prevention is a more viable and cost-effective solution than injury treatment. Injury categorization allows intervention to be undertaken at appropriate steps, and more importantly allows appropriate interventions that serve to adequately address the issue at hand. Given that hand and wrist injuries constitute the second highest overall reported type of injury in combat athletes following head trauma, accurate categorization and description of hand/wrist injuries in these athletes should allow us to design appropriate interventions in this rapidly expanding sport.(21, 109, 110)

Sports that employ only striking (i.e., boxing) had the highest overall proportion of fractures at the fingers, including the phalanges and the metacarpals. This trend was mirrored in other high intensity striking sports, such as karate, Muay Thai and krav maga, but was not found in sports that either employ only throws (i.e., jiu jitsu) or employ a lower overall frequency of closed fist strikes (i.e., judo, MMA, taekwondo and kickboxing). Unsurprisingly, in krav maga (which does not traditionally use any hand protection) there was a wide distribution of fractures throughout the entire hand and wrist. Joint injuries were also most common in striking sports, highest once again in boxers and specifically highest at the finger CMC joints. This finding is not surprising since the biomechanics of a closed fist punch transmits force from the metacarpals to the CMC joints and carpal bones. Boxers also had the highest rate of extensor hood rupture and overall chronic injuries, again most likely related to repetitive and continuous impact over the finger MCP joints. This contrasts with sports that have a lower intensity of striking or employ throws, where these types of injuries are nearly non-existent.

Additionally, the injury breakdown demonstrates that a significantly higher proportion of hand and wrist injuries are documented during training rather than during matches/tournaments. This correlates with the anticipated number of hours a combat athlete spends in training versus time spent in matches and tournaments. Taken together, this implies that interventions aimed at preventing hand and wrist injury should be implemented during training rather than solely during matches.

This systematic review is one of the largest and most specific to hand and wrist injuries in a wide variety of combat sports, however it is by no means comprehensive due to the rigid inclusion/exclusion criteria that were applied. Most papers addressing these types of injuries in combat athletes are individual case reports and case series. These papers therefore lack an accurate representation of injuries per training hours or matches/tournaments participated in, and/or the number of total screened athletes and thereby affects the strength of our conclusions. This also prevents an accurate calculation of the overall incidence and prevalence of injury. One single paper on krav maga constituted a large portion of documented injuries (28), which may have biased proportion calculations and trends. Regardless of these limitations, certain generalizations and trends come to light about the nature of injuries in the subcategories that were explored given the detailed breakdown provided above.

Taken together, these findings imply that the amount of force applied to the closed fist in striking sports is not only substantial, but also likely cumulative. Therefore, intervention aimed at injury prevention at the MCP/phalanx-impact surface interface, which can potentially mitigate acute and cumulative chronic injuries, would be of substantial benefit in these athletes.

Chapter 3. Sensor validation

Eva M. Gusnowski, Gregory W. Spangenberg, Daniel Langohr, Kenneth Faber and Ruby Grewal

3.1 Introduction

To directly quantify the amount of force experienced at the MCP/phalanx interface with a hand wrap, we developed an innovative method of force and impact measurement using a commercially available load cell. In order to ensure the load cell would provide measurements and information as expected, we validated the sensor in a dynamic striking scenario against a pre-calibrated external load cell. The following section describes the method and results of the sensor validation.

3.2 Materials and methods

3.2.1 Force measurements during striking

A single pressure sensor with a 1000 N maximum capacitance and 500 Hz detection was attached to an aluminum panel mounted between two angle iron sections and an aluminum mounting fixture which was leaned against a concrete wall (Figure 3.1). A commercially available square striking pad with an ethylene vinyl acetate (EVA) interior (Wesing, Fujian, China) measuring 25.0 cm by 25.0 cm by 4.0 cm and weighing 0.200 kilograms (kg) was attached to a piece of solid pine with a central cut-out to permit attachment to the load cell mounting post. This was secured over the pressure sensor to allow direct striking by a single athlete (Figure 3.1). Foam density was not provided by the manufacturer but is estimated at 80 kg/m^3 based on reported weight and dimensions.

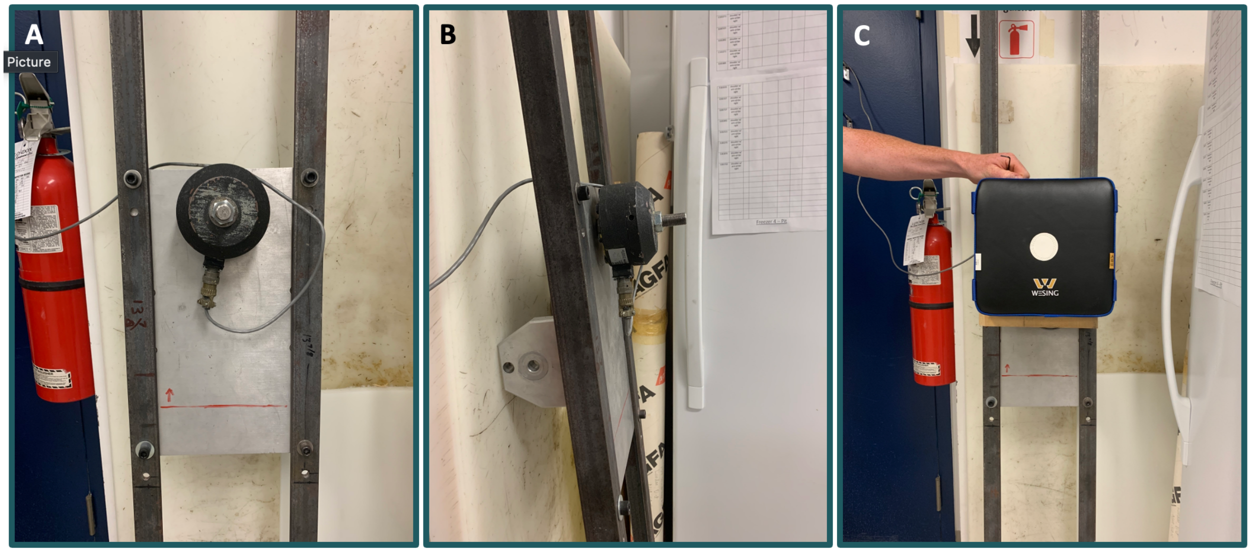

Figure 3.1. Mounted pressure sensor and striking pad used in sensor validation. A. Front and B. lateral views of mounted pressure sensor. C. Striking pad placement over mounted sensor.

Two commercially available sensors were used for comparative force measurements. The novel loadpad™ sensor (model GmbH HwRev2, firmware version SwRev3.1.7.Ca.Ca3, novel.de) is a load cell sensor that measures the force between two objects via measurement of sensor deformation and strain which is converted into an electronic signal and measurement of total force. The sensor measures 10 cm x 5 cm with an attached Bluetooth transmitter (Figure 3.2) and a detection capacity of 100 Hz. Based on previous studies of contact time between the glove and bag during punching of approximately 25 milliseconds (equivalent to 50 Hz), the capture rate of this sensor reaches the minimum requirement as directed by the Nyquist principal. The sensor was pre-calibrated by novel.de prior to use in this study. The novel loadpad resolution was set at 2.5 N, with a maximum force of 625 N captured at this resolution.(111) Any force detected above this maximum value is dynamically adapted to a higher temporary resolution (resolution = measured force x 0.004) by the software program. Final values were automatically rounded to the nearest 2.5 N and measured every 5 milliseconds. The StrikeTec™ sensor is a commercially available accelerometer that is calibrated for striking during combat sports (Figure 3.2). These sensors provide information about forward force and therefore indirectly measure effort (or force) through acceleration, taking into account some assumptions about the characteristics of the body in motion. Both sensors have wireless Bluetooth technology and have validated smart phone mobile applications for use with Apple (loadsol™ iOS version 1.4.94, novel.de) or Android (StrikeTec Mobile App™ version 1.4.8, Elliott Fight Dynamics, LLC).

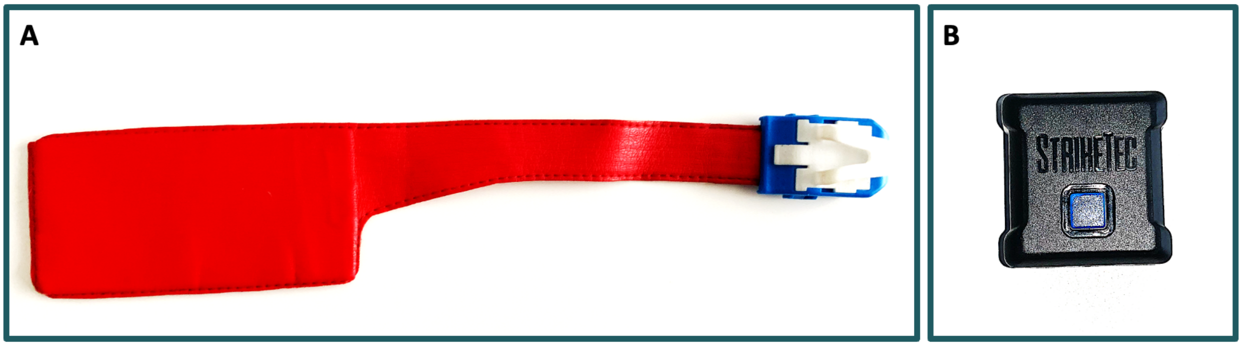

Figure 3.2. Sensors used in this study for impact load (novel loadpad) and forward effort (StrikeTec). A. Novel loadpad sensor (red) measuring 10 cm by 5 cm by 4 mm with a non-sensing extension and Bluetooth transmitter (blue and white). B. StrikeTec sensor measuring 2.5 cm by 2.5 cm by 1 cm.

A single combat athlete participated in the sensor validation. The athlete was a right-hand dominant 59.1 kg female with 6 years of kickboxing/boxing/combat sport experience. The novel loadpad sensor was placed directly over the index through small finger MCP joints and proximal phalanges of the right hand, aligned ulnarly with the small finger PIP joint, and secured with a single layer of 10.16 cm self-adherent wrap. (Figure 3.3). The StrikeTec sensor was placed directly overlying the dorsum of the distal radius, just proximal to Lister's tubercle and was also secured with a single layer of 10.16 cm self-adherent wrap.

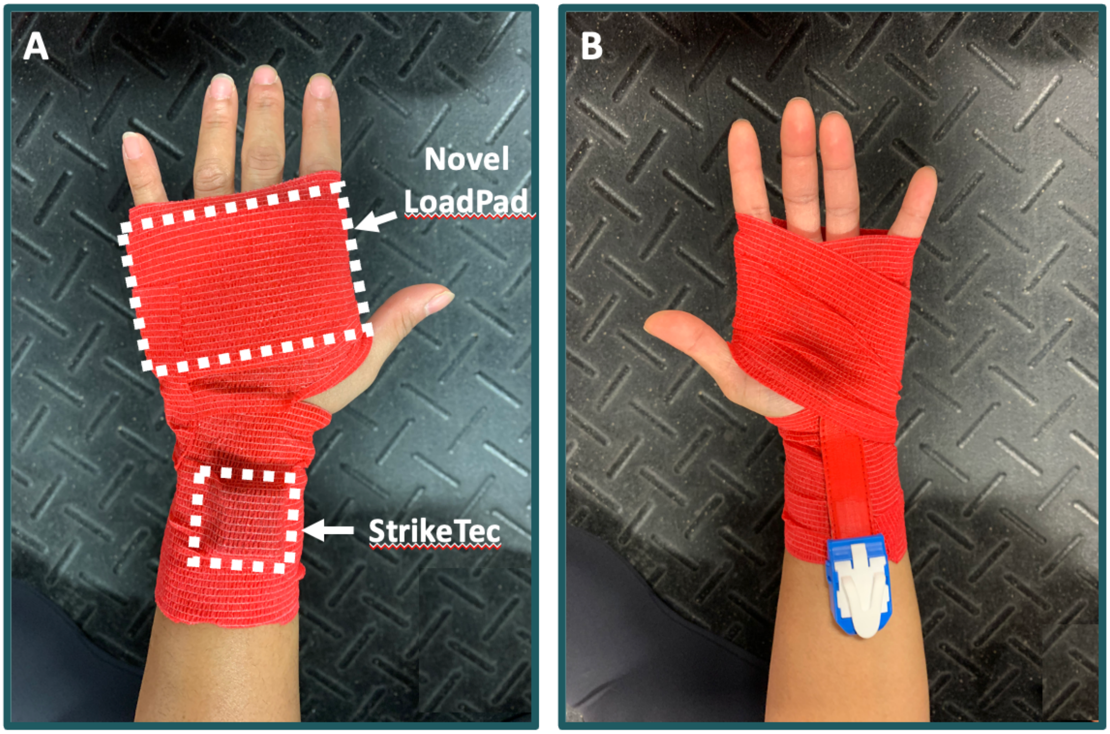

Figure 3.3. Left hand of an athlete demonstrating placement of novel loadpad and StrikeTec sensors held with self-adhesive wrap before striking protocol. A. Dorsal side of hand with outlines delineating novel loadpad and StrikeTec sensors under the self-adhesive wrap. B. Palmar side of hand with free extension and Bluetooth transmitter of the novel loadpad.

A 180 inch (457.2 cm) linear wrap (Guerrero model wraps; 70% poly-viscose/30% nylon; Rival Boxing, Montreal, Quebec, Canada; Figure 3.4) was then applied to the right hand in a standardized fashion: the wrap is anchored at the wrist with 3 revolutions, sequentially wrapped between the second through fourth finger web spaces, wrapped around the MCPs/metacarpals with 3 revolutions, then finally wrapped around the thumb/ulnar hand and secured at the wrist (Figure 3.5). The novel loadpad sensor was zeroed after wrapping but prior to all punches being thrown. Ten right-hand crosses were then thrown onto the center of the striking pad/sensor. A standard 16-ounce boxing glove (Cleto Reyes Boxing, Mexico City, Mexico) was then placed onto the right hand, and the novel loadpad sensor again was zeroed (Figure 3.6). Ten right-hand crosses were then thrown onto the center of the striking pad/sensor with the glove.

Figure 3.4. Left hand demonstrating final wrapping of the 180-inch (457.2 cm) Guerrero style Rival linear wraps. A. Dorsal side of hand. B. Radial side of hand. C. Palmar side of hand.

Figure 3.5. Left hand of an athlete demonstrating placement of linear wraps over sensors. A. Dorsal side of hand. B. Radial side of hand. C. Palmar side of hand.

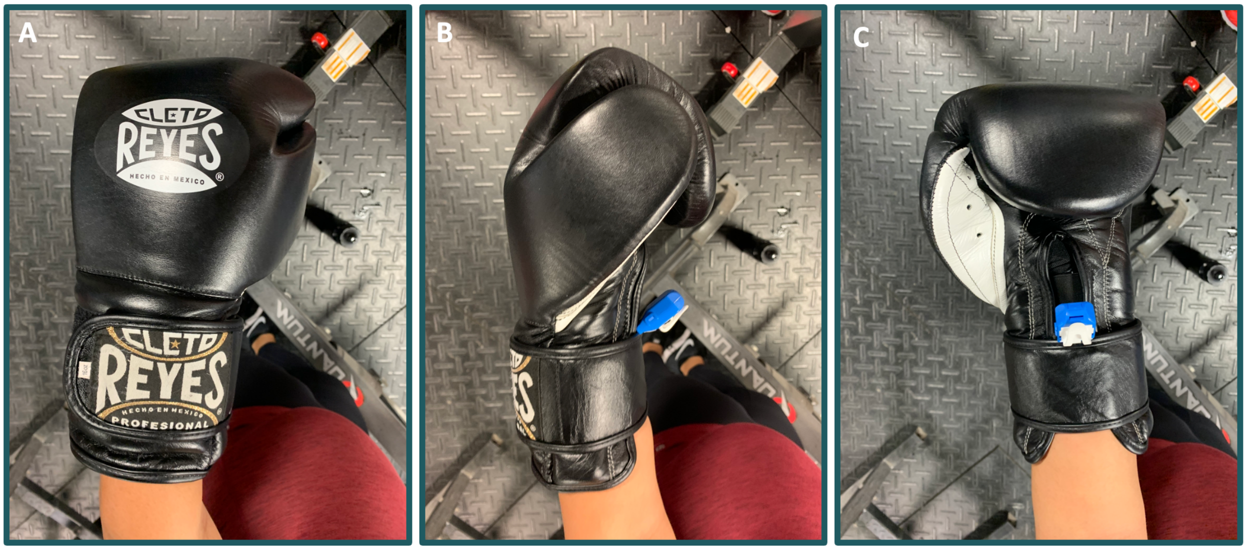

Figure 3.6. Left hand of an athlete demonstrating placement of boxing glove over linear wraps and sensors. A. Dorsal side of glove. B. Radial side of glove. C. Palmar side of glove.

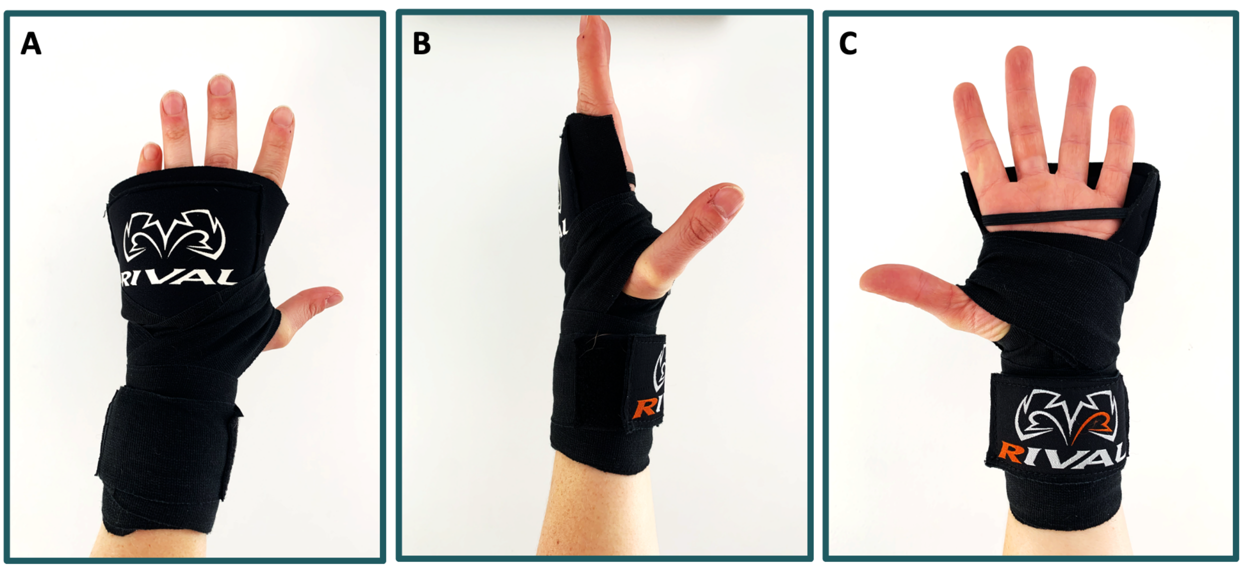

Figure 3.7. Left hand demonstrating modification to palmar side of gel wraps. Note that the only material over the striking surface is the gel portion of the wrap, with no additional material added over this area. A. Dorsal side of wrap. B. Radial side of wrap. C. Palmar side of wrap.

The glove and linear wrap were then removed and a 150-inch (381 cm) version of the Rival Gel Wrap (8 mm gel insert within neoprene glove with 125 cm Mexican wrap attachment; Rival Boxing, Montreal, Quebec, Canada) was then applied over the novel loadpad and StrikeTec sensors. The Rival Gel Wraps were modified on the palmar side to allow accommodation of the novel loadpad sensor (Figure 3.7), but the gel portion of the wrap was not modified. The wrap was placed over the novel loadpad sensor, with no additional circumferential wraps placed over the gel portion. The novel loadpad sensor was zeroed after wrapping, prior to all punches being thrown. Again, ten right-hand crosses were thrown onto the center of the striking pad/sensor and repeated with the 16-ounce boxing glove as above.

Following each striking protocol, the gloves and wraps were removed to allow inspection of the position of the sensors to ensure there was no change in position (Figure 3.8). Any change in position of the sensor was considered sufficient reason to exclude the series of strikes. No change in position was noted during the above striking protocol and all strikes were considered usable data in the analysis.

Figure 3.8. Left hand of an athlete demonstrating maintenance of placement of novel loadpad and StrikeTec sensors held with self-adhesive wrap after completing striking protocol. A. Dorsal side of hand. B. Palmar side of hand.

3.2.2 Data export and analysis

The loadsol application for iOS was used to capture all force measurements from the novel loadpad sensor. Graphic data was manually inspected in the loadsol application to identify maximum force peaks corresponding to strikes (Figure 3.9). Numeric striking data including time stamps and force values was exported into text files where an open-source algorithm was used to account for background drift of the novel loadpad sensor (Figure 3.10).(112) All previously identified strike peaks were then manually identified in the drift-adjusted files and the adjusted force values were recorded and imported into Microsoft Excel for subsequent analysis.

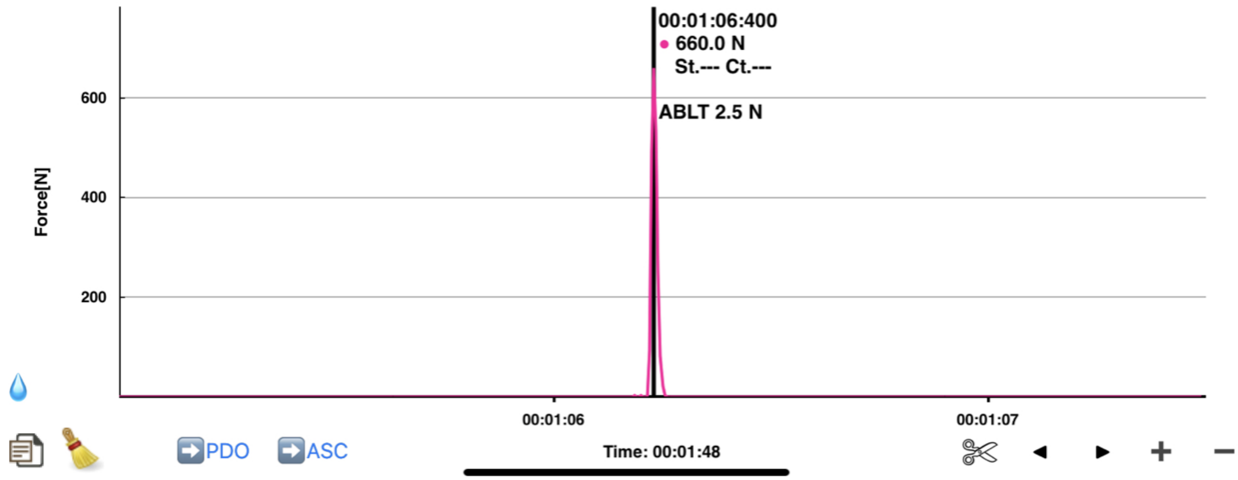

Figure 3.9. Graphic representation of a strike peak in the loadsol iOS application.

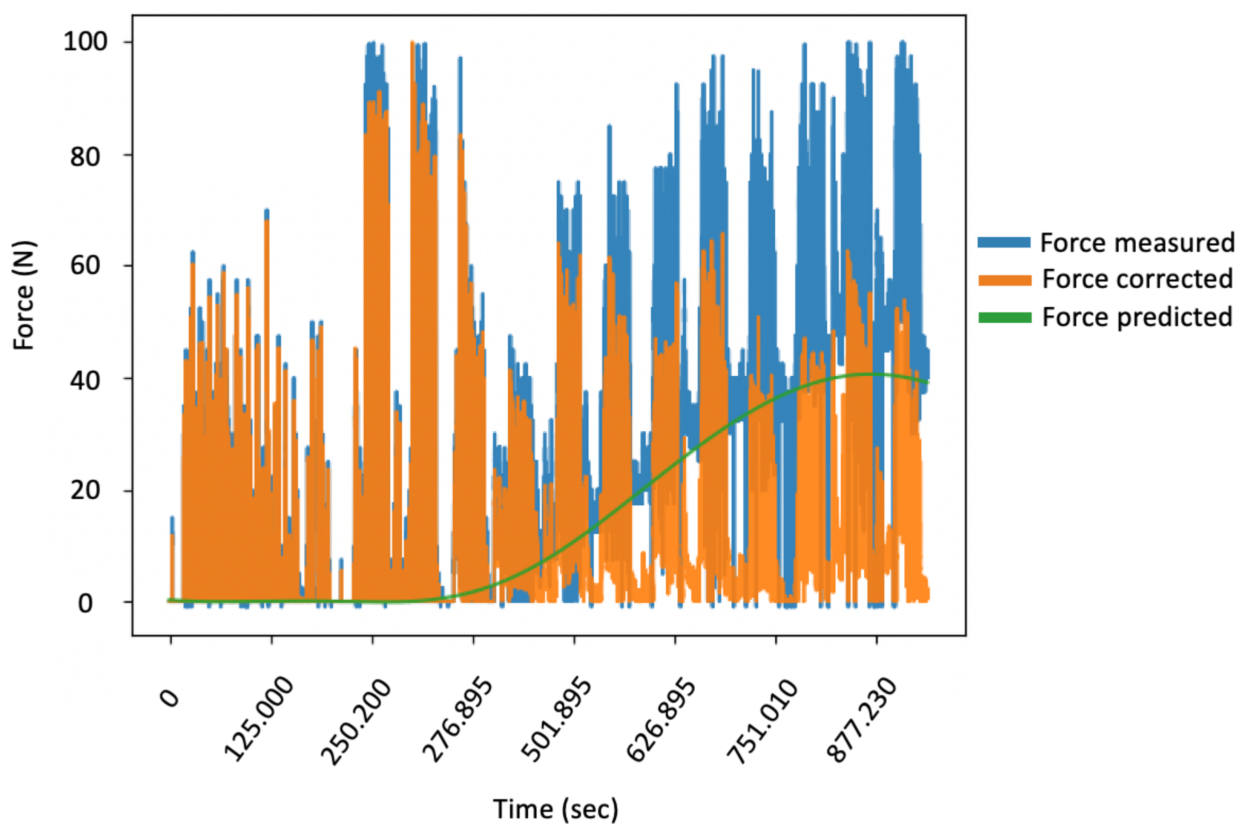

Figure 3.10. Graphic representation of strike peaks after drift correction applied to force values in a representative athlete.

The StrikeTec measurements were recorded in the StrikeTec mobile application and transferred to Microsoft Excel for analysis. The force measurement output of pound-force (lbF) was converted to Newtons (1 lbF = 4.448 N).

The mean and standard deviation for each subtype was calculated and used for analysis. A Cronbach's alpha score was used to compare paired force values between the various sensors during strikes. An unpaired two-tailed t-test assuming unequal variances was used for comparison. Significance was defined as a p-value of 0.05.

3.3 Results

The protocol was performed using 4 scenarios to determine the relative accuracy of the novel loadpad and StrikeTec sensors compared to the pre-validated Instron load cell during a dynamic striking event. A total of n = 10 strikes were thrown for each of the linear wrap, linear wrap + glove and gel wrap + glove scenarios and n = 11 strikes for the gel wrap scenario. Mean forces for the novel loadpad, StrikeTec sensor and Instron load cell are shown in Table 3.1. Cronbach's alpha scores for the paired measurements were calculated and all measured at 0.75 or greater, demonstrating good to excellent agreement between the sensors. The StrikeTec sensors demonstrated the highest overall reported force in all 4 scenarios, followed by the external load cell and finally by the novel loadpad. The mean difference between the Instron load cell and the other two sensors are presented in Table 3.1. The use of boxing gloves resulted in a decrease in the amount of force detected by the novel loadpad compared to wraps alone regardless of which type of wrap was used.

	Novel mean force N (SD)	Instron mean force in N (SD)	Difference (Instron - Novel) in N (SD)	StrikeTec mean force N (SD)	Difference (Instron - StrikeTec) in N (SD)
Linear wrap (n=10)	563.3 (73.4)	694.2 (128.3)	130.9 (74.6)	838.9 (125.7)	144.7 (70.4)
Gel wrap (n = 11)	617.3 (80.0)	680.9 (124.7)	63.6 (93.1)	953.1 (80.1)	272.2 (134.1)
Linear wrap + glove (n = 10)	382.5 (63.5)	825.3 (113.6)	442.8 (63.7)	967.4 (115.6)	142.1 (97.5)
Gel wrap + glove (n = 10)	394.3 (34.0)	858.3 (47.1)	464.1 (29.8)	903.4 (38.7)	45.0 (42.4)

Table 3.1. Difference in mean force for hand load impact (Novel), effort (StrikeTec) and validated load cell (Instron). Values are given in mean Newtons (N) and standard deviation (SD).

Statistical comparison of the mean force values measured by the three sensors demonstrated no statistically significant difference except for a comparison of the StrikeTec sensors between the linear wrap (mean = 839.9 N) and gel wrap (mean = 953.1 N) striking protocol (p = 0.0214; Table 3.2). Despite this statistically significant increase in measured effort in the gel wrap subgroup compared to the linear wrap subgroup, no significant difference was found by the novel loadpad in the gel wrap subgroup (mean = 617.3 N) versus the linear wrap subgroup (mean = 563.3 N).

	Wraps only			With glove		
	Linear wrap (n = 10)	Gel wrap (n = 11)	p-value	Linear wrap (n = 10)	Gel wrap (n = 10)	p-value
Novel mean force in N (SD)	563.3 (73.4)	617.3 (80.0)	0.1226	382.5 (63.5)	394.3 (34.0)	0.6122
StrikeTec mean force in N (SD)	838.9 (125.7)	953.1 (80.1) ^	**0.0214 ***	967.4 (115.6) ^	903.4 (38.7)	0.1139
Instron mean force in N (SD)	694.2 (128.3)	680.9 (124.7)	0.813	825.3 (113.6)	858.3 (47.1)	0.4067

Table 3.2. Mean overall force comparisons for effort (StrikeTec), hand load impact (Novel) and validated load cell (Instron). Values are given in mean Newtons (N) and standard

deviation (SD). (^) indicates the higher mean for the StrikeTec force for the gel versus linear wraps. (*) indicates statistical significance at α = 0.05.

3.4 Discussion

Previous studies of protective gear in combat athletes have largely investigated the amount of forward force and/or impact load that can be generated against an opponent. The ease of measurement in these studies allows the use of external load cells for all measurements and can largely ignore the amount of force that is experienced by the hand and wrist. The application of a load cell at the MCP/phalanx wrap interface is a novel concept in force measurement to investigate the amount of force transmitted to the athlete's hand and wrist. Additionally, subtle changes in the position and therefore biomechanics of the hand/wrist during striking in real life scenarios will affect the forces experienced by the hand compared to testing with a static model. Accurate force testing in combat athletes in an active setting is integral to understanding experienced force dynamics and designs for protective gear.

The use of a load cell is commonly used in force measurements, and the novel loadpad force sensor has been used in previous studies to investigate the amount of force between two objects.(113) The novel loadpad sensor and StrikeTec wrist accelerometers are provided pre-calibrated and subsequent sensor calibration was not required. Herein we have tested the novel loadpad and StrikeTec sensors against a pre-validated and calibrated external load cell to compare its overall efficacy in force experienced at the hand/wrap interface.

The highest level of force in this validation study was detected by the StrikeTec accelerometers as compared to the external load cell and the novel loadpad. As this study used wraps +/- gloves as well as a striking pad between the Instron and novel loadpad as a protective measure against athlete injury, this finding is not unanticipated. If the degree of impact on the front and back surfaces of the striking pad are assumed to be equivalent,(114) the remaining force difference is assumed to be from energy absorption by the hand wraps, as the novel loadpad sensor was not altered or changed during the protocol. The difference in force detected by the Instron load cell and novel loadpad with only wraps used, which would most closely replicate a bare-knuckle punch, revealed an overall mean difference of 130.9 N (standard deviation 74.6) in the linear wraps and 63.6 N (standard deviation 93.1) in the gel wraps. This resulted in an overall difference of 18.9% (563.3 N/694.2 N) with the linear wraps and 9.1% (617.3 N/680.9 N) with the gel wraps. Again, given the presence of the protective elements used and likely small differences in the accuracy of strikes directly centered over the Instron load cell, this demonstrates that the use of the novel loadpad is of sufficient capacity to detect the force impact at the MCP/phalanx and wrap interface.

There have been investigations of various types of gloves and their overall effect on impact force, however these studies focused on forward impact/force rather than retrograde force transmitted to the hand and wrist. In a study looking at traditional fingerless MMA gloves (4 ounce) versus enclosed boxing gloves (16 ounce), the authors demonstrated that damping of forward force increases with increasing size and weight of gloves, likely owing to the increased thickness of foam required to achieve a higher weight.(115) However, in a study investigating different brands and sizes of boxing gloves, the largest difference in damping was observed with the composition of the glove padding rather than the ultimate size and weight, although lighter gloves of a given composition performed more poorly than their higher weight counterparts. (116) In keeping with this damping property of protective gear, our results demonstrated a dramatic reduction of force detected at the hand-wrap interface when gloves were worn. The mean differences between the novel loadpad and Instron load cell increased up to 442.8 N with the use of a glove and linear wraps (compared to 130.9 N with linear wraps alone) and 464.1 N with the use of a glove and gel wraps (compared to 63.6 N with gel wraps alone).

Overall, these results demonstrate that the novel loadpad can feasibly be used in further testing for force measurements at the hand/wrap interface. Additionally, herein it is also demonstrated that the use of gloves dramatically decreases the retrograde force experienced at the hand and is an important element of combat athlete protection.

Chapter 4. Force analysis in combat athletes

Eva M. Gusnowski, Gregory W. Spangenberg, Daniel Langohr, Kenneth Faber and Ruby Grewal

4.1 Introduction

Hand protection is an integral part in the prevention of hand and wrist injury in combat athletes. Although many different types of boxing gloves have been tested to look at forward force generation and energy dissipation, no studies to date have looked at the protective capacity of different types of hand wraps for the combat athlete. Herein we will look at the relative energy absorption by two different types of commercially available hand wraps in a dynamic setting.

4.2 Materials and methods

4.2.1 Recruitment

Combat athletes were recruited for participation in this study by placement of recruitment posters in a local boxing gym (Bushido Boxing, London, Ontario, Canada; United Boxing Club, Winnipeg, Manitoba, Canada) where the study was to be performed (Appendix B). Participants were recruited on a volunteer basis that was initiated by the athlete, and active recruitment was not performed. Written informed consent was obtained by one of the researchers (E.M.G.). Athletes were eligible for the study if they were 18 years of age or older, were able to complete an English questionnaire and provide informed consent to participate. Exclusion criteria included acute or subacute (< 3 months) upper extremity injury or inability to provide consent. All experience levels were included in the study. Patient demographics were collected, including age, sex, handedness/boxing stance, previous hand/wrist injury and experience level.

4.2.2 Study Design

This study was performed as a prospective cross over study with all athletes participating in both subgroups, wherein all athlete measurements were compared between their own subgroups for the analysis. The athletes were brought to the gym on two separate days to perform the strikes to prevent a fatigue bias between the two types of wraps. Athletes were randomized to complete either the linear hand wraps or gel hand wraps on day 1 versus day 2 using an online random number generator.(117) The order of the six standard punches was also randomized on day 1, and the same pattern was completed on day 2.

4.2.3 Sensor placement and wrap application

Two commercially available sensors were used for comparative force measurements as described in section 3.2.1 (novel loadpad sensor and loadsol mobile application, novel.de; StrikeTec sensors and StrikeTec mobile application, StrikeTec). Placement and alignment of the novel loadpad sensor over the MCP joints/proximal phalanges and StrikeTec sensors over the wrist dorsum as well as securing of the sensors with self-adhesive wrap was also performed as previously described (Section 3.2.1; Figure 3.3)

Linear wraps: Following sensor placement, a 180-inch (457.2 cm) Guerrero wrap (70% poly-viscose/30% nylon; Rival Boxing, Montreal, Quebec, Canada) was then applied to the hand in a standardized fashion: the wrap is anchored at the wrist with 3 revolutions, sequentially wrapped between the second, third and fourth finger web spaces, wrapped around the MCPs/metacarpals with 3 revolutions, then finally wrapped around the thumb/ulnar hand and secured at the wrist (Figure 3.4). A standard 16-ounce boxing glove (Cleto Reyes Boxing, Mexico City, Mexico) was then placed onto the right hand, and the novel loadpad sensor was zeroed.

Gel wraps: Following sensor placement, a 150-inch (381 cm) Rival Gel Wrap (8 mm thick solid gel with an attached 381 cm Mexican style linear wrap; Rival Boxing, Montreal, Quebec, Canada) was then applied over the novel loadpad and StrikeTec sensors. The Rival Gel Wraps were modified on the palmar side to allow accommodation of the novel loadpad sensor (Figure 3.7) but the gel portion of the wrap was not modified. The gel portion of the wrap was placed over the novel loadpad sensor, with no additional circumferential wraps placed over the gel portion or novel loadpad. The novel loadpad sensor was then zeroed after wrapping, prior to all punches being thrown. A standard 16-ounce boxing glove (Cleto Reyes Boxing, Mexico City, Mexico) was then placed onto the hand, and the novel loadpad sensor was zeroed. All participants used the same gloves for the analysis and threw strikes on an 18-inch (45.72 cm) AquaBag Training Bag, filled to a total weight of 45.8 kg (AquaBag, Gloversville, New York, USA) to maintain consistency. Bag height was adjusted to athlete preference before each session.

4.2.4 Force measurements

After the sensor and randomized hand wrap was applied to the appropriate hand for testing and the sensor zeroed, the athletes performed a 3-minute shadow boxing warm up. Following the warmup, the athlete was guided through the randomized order of punches and instructed to perform the strikes as they would during a normal training session. Each punch was thrown for 30 seconds of effort followed by 30 seconds of rest and the cycle was repeated 4 times. Following cycle completion, the wrap was removed and the sensor was inspected to ensure there was no change in position during the striking protocol. The sensors, wrap and glove were then switched to the contralateral hand and the protocol as outlined above was repeated.

4.2.5 Data export and analysis

Data export, localization of peak forces and drift adjustment was performed by the standardized protocol described in section 3.2.2. All means were compared by a two-tailed t-test assuming unequal variances. Significance was defined at $p = 0.05$.

4.3 Results

4.3.1 Athlete recruitment

A total of 14 athletes were recruited for initial participation in this study (Figure 4.1). Two athletes were unable to complete the second day of testing due to COVID-19 pandemic restrictions. Two athletes completed both sessions but data output was corrupted and could not be retrieved for analysis. Novel loadpad sensor malfunction prevented 4 athletes from completing their second day of testing. A total of 6 combat athletes completed both days of strike testing for data analysis.

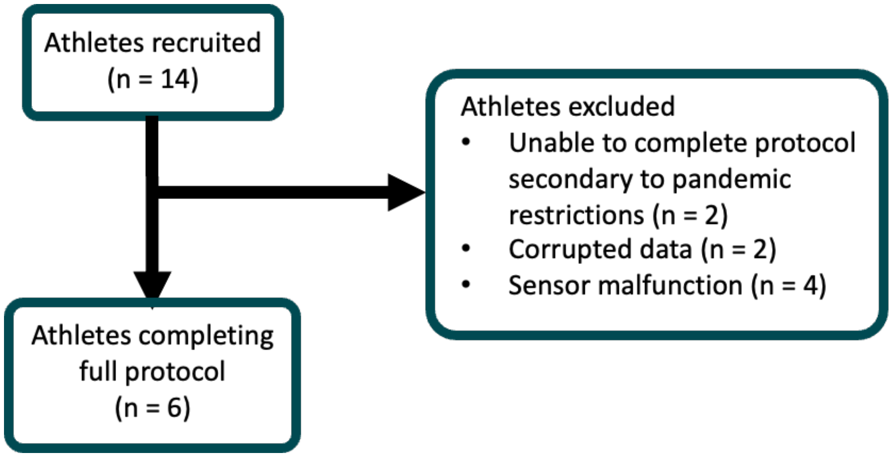

Figure 4.1 Flow diagram of athletes recruited and reasons for exclusion from testing.

4.3.2 Athlete demographics

Six combat athletes completed both days of the striking protocol of this study, with demographics as shown in Table 4.1 below. The athlete participants included 4 males, 1 female and 1 transfemale, with an average age of 31.2 years (range 20 to 40 years). Five of the athletes identified boxing as their main sport of choice, and 1 athlete participated primarily in Muay Thai. The athletes had a broad range of experience, with an average of 76.5 months (range 5 to 177 months). Four of the participants identified as recreational athletes, whereas 2 had participated in amateur fights/tournaments. All athletes used a standard orthodox stance (left hand/foot leading). Two of the athletes (Athlete B and Athlete D) disclosed remote upper extremity injuries. Height and weight were self-reported by the athletes in inches/pounds and converted to standardized metric measurements. Weight categories are provided as per the most recent published standardized competitive weight divisions from Boxing Canada.(118)

Athlete	Gender	Age (years)	Primary Sport	Experience	Experience (years/ months)	Stance	Handedness	Weight (kg)	Weight Class	Height (cm)	History of hand/wrist injury
A	Female	34	Boxing	Recreational	4 y 7 m	Orthodox	Right	59.5	Light weight	162.56	None
B	Male	26	Boxing	Amateur	3 y 6 m	Orthodox	Did not answer	83.2	Heavy weight	190.5	Non-specified fracture right hand 2011
C	Male	20	Boxing	Amateur	10 y	Orthodox	Right	63.6	Light welter weight	172.72	None
D	Male	27	Boxing	Recreational	5 m	Orthodox	Right	95.5	Super heavy weight	177.8	Left wrist strain 10 years prior
E	Transfemale	40	Boxing	Recreational	5 y	Orthodox	Did not answer	101.4	Heavy weight	190.5	None
F	Male	40	Muay thai	Recreational	14 y 9 m	Orthodox	Did not answer	72.7	Middle weight	177.8	None

Table 4.1. Demographics of athletes that completed both days of strike testing.

4.3.3 Athlete number randomizations

Table 4.2 demonstrates the randomized order of wraps, hand and strikes that each of the 6 athletes completed. Despite computer randomization, all athletes that completed the protocol performed the striking regimen using the gel wraps on the first day of testing and the linear wraps on the second day.

Athlete	Wraps Day 1	Wraps Day 2	1st hand	Strike order	2nd Hand	Strike order
A	Gel	Linear	Rear (right)	Uppercut Hook Cross	Lead (left)	Jab Hook Uppercut
B	Gel	Linear	Lead (left)	Uppercut Jab Hook	Rear (right)	Cross Hook Uppercut
C	Gel	Linear	Lead (left)	Uppercut Jab Hook	Rear (right)	Hook Cross Uppercut
D	Gel	Linear	Rear (right)	Cross Uppercut Hook	Lead (left)	Uppercut Jab Hook
E	Gel	Linear	Rear (right)	Cross Hook Uppercut	Lead (left)	Hook Uppercut Jab
F	Gel	Linear	Rear (right)	Uppercut Cross Hook	Lead (left)	Jab Uppercut Hook

Table 4.2. Randomization parameters for athletes that completed both days of testing.

4.3.4 Athlete force measurements

The results for each individual athlete that completed both days of the testing protocol are provided in sections 4.3.4A through 4.3.4F below.

4.3.4A Athlete A

Athlete A was a 34-year-old female with 55 months of recreational boxing experience, orthodox stance, and a self-reported weight of 59.5 kg (Table 4.1). Athlete A had a statistically significant higher value of measured forward effort for the gel hand wraps in the jab, lead hook and lead uppercut strikes ($p < 0.0001$ for all three strikes), and for the linear wraps in the cross, rear hook and rear uppercut strikes ($p < 0.001$ for all three strikes; Table 4.3). A statistically significantly higher force was measured by the novel loadpad in all strikes, with higher measurements found for the linear wraps ($p < 0.01$ for all measurements). The lowest absolute difference in impact was measured between the gel and linear wraps in the rear hook and rear uppercut strikes (Table 4.3, Figure 4.2). The mean force for each individual 30 second round is demonstrated in Tables 4.4 and 4.5 and presented in Figures 4.3 and 4.4.

Athlete A	StrikeTec Gel Wraps (Mean N (SD))	StrikeTec Linear Wraps (Mean N (SD))	StrikeTec p-value	Novel Gel Wraps (Mean N (SD))	Novel Linear Wraps (Mean N (SD))	Novel p-value
Jab	723.4 (83.8) ^	654.0 (49.9)	<0.0001 *	70.0 (28.7)	193.9 (37.3)	<0.0001 *
Cross	735.7 (70.5)	774.5 (61.7) ^	0.0009 *	55.0 (18.5)	102.1 (33.6)	<0.0001 *
Lead Hook	942.5 (107.1) ^	858.4 (82.6)	<0.0001 *	38.0 (20.6)	200.0 (62.8)	<0.0001 *
Rear Hook	856.3 (89.1)	937.2 (90.5) ^	<0.0001 *	53.9 (22.8)	64.4 (19.9)	0.0097 *
Lead Uppercut	930.4 (83.2) ^	826.5 (69.1)	<0.0001 *	37.7 (12.7)	193.2 (58.6)	<0.0001 *
Rear Uppercut	823.8 (63.3)	880.4 (50.4) ^	<0.0001 *	17.5 (5.0)	41.6 (10.5)	<0.0001 *

Table 4.3. Mean overall force comparisons for effort (StrikeTec) and impact (Novel) for Athlete A. Values are given in mean Newtons (N) and standard deviation (SD). (^) indicates the higher mean for the StrikeTec force for the gel versus linear wraps. (*) indicates statistical significance at p = 0.05.

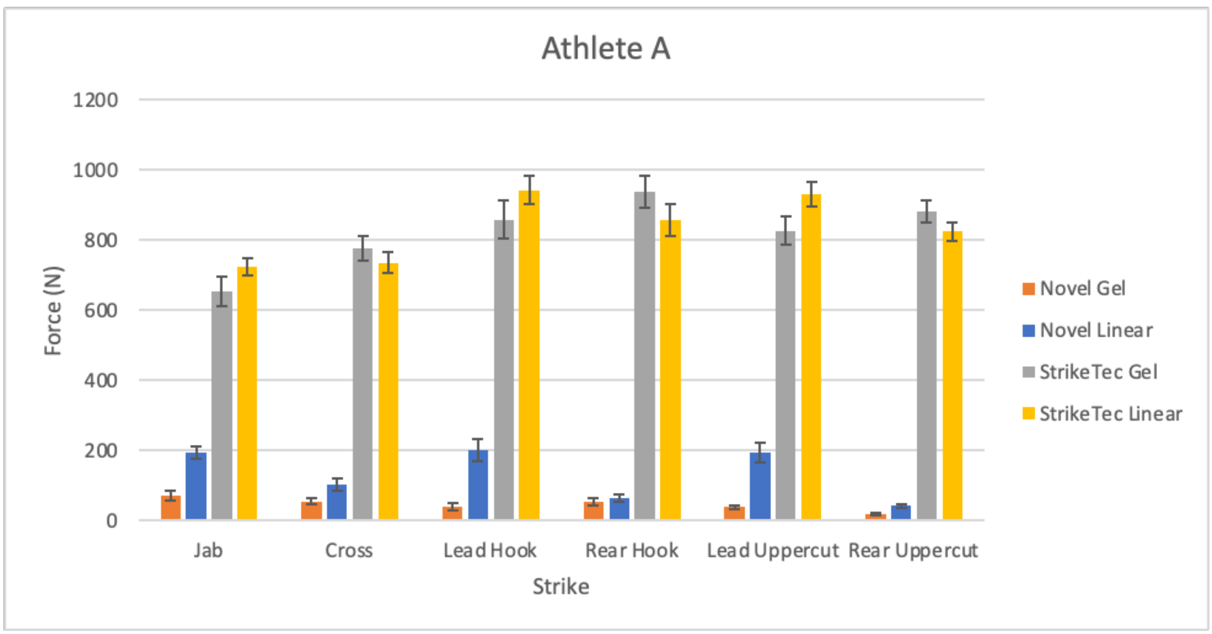

Figure 4.2. Mean overall force comparisons for impact (Novel) and effort (StrikeTec) for Athlete A. Values are presented in mean Newtons (N) and standard deviation (error bars).

Athlete A Linear Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	191.3 (42.6)	19	673.6 (50.8)	19
	2	188.2 (38.7)	22	645.0 (41.3)	22
	3	179.6 (24.5)	19	635.9 (58.5)	19
	4	214.3 (33.8)	22	661.8 (44.2)	22
Cross	1	96.7 (34.8)	19	771.2 (64.9)	19
	2	102.8 (27.9)	19	762.8 (58.7)	19
	3	115.9 (35.4)	17	771.3 (69.5)	18
	4	93.0 (34.7)	16	796.0 (51.7)	16
Lead Hook	1	146.5 (21.4)	15	949.5 (53.3)	15
	2	164.7 (29.9)	19	832.3 (54.9)	19
	3	237.3 (73.6)	16	833.5 (92.5)	16
	4	243.9 (46.5)	20	834.7 (68.8)	20
Rear Hook	1	70.7 (13.9)	14	969.4 (120.8)	14
	2	66.6 (28.4)	17	911.6 (86.4)	17
	3	59.9 (16.9)	15	913.1 (56.9)	15
	4	60.3 (14.8)	14	962.1 (81.1)	14
Lead Upper	1	148.4 (30.7)	17	831.0 (76.8)	17
	2	160.8 (23.9)	18	837.0 (67.9)	18
	3	230.3 (63.5)	17	783.1 (62.1)	18
	4	235.1 (48.5	17	856.7 (49.8)	17
Rear Upper	1	42.8 (13.0)	13	882.1 (54.4)	13
	2	33.8 (7.3)	17	893.0 (61.5)	16
	3	45.3 (9.1)	16	881.6 (43.1)	16
	4	45.7 (8.1)	14	863.0 (39.5)	14

Table 4.4. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete A wearing linear hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD).

Athlete A Gel Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	80.6 (37.5)	18	741.2 (77.3)	19
	2	79.4 (39.4)	17	750.2 (93.5)	17
	3	65.4 (16.2)	16	699.8 (73.4)	16
	4	55.3 (19.9)	19	701.6 (84.0)	19
Cross	1	58.5 (17.8)	12	722.1 (70.4)	12
	2	61.6 (19.4)	16	768.4 (62.7)	16
	3	52.8 (21.2)	16	747.9 (76.0)	16
	4	48.2 (13.7)	17	703.1 (60.2)	17
Lead Hook	1	48.6 (37.1)	15	894.1 (165.6)	16
	2	34.2 (8.1)	15	946.6 (65.0)	15
	3	39.8 (9.2)	16	949.7 (85.2)	16
	4	29.3 (8.3)	15	979.7 (68.6)	16
Rear Hook	1	76.9 (20.7)	12	921.9 (92.6)	12
	2	68.9 (11.2)	12	918.8 (57.3)	11
	3	44.6 (13.1)	15	829.0 (69.8)	14
	4	32.8 (12.1)	15	783.5 (46.2)	15
Lead Uppercut	1	50.3 (12.1)	16	906.8 (84.0)	15
	2	34.0 (8.9)	13	938.0 (78.8)	15
	3	27.1 (5.4)	16	909.5 (39.3)	15
	4	38.6 (10.1)	17	970.0 (109.6)	14
Rear Uppercut	1	19.3 (4.8)	11	881.2 (50.5)	10
	2	19.6 (7.0)	12	826.3 (46.9)	12
	3	16.0 (4.8)	14	829.9 (43.8)	14
	4	16.2 (2.7)	17	783.1 (68.1)	17

Table 4.5. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete A wearing gel hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD).

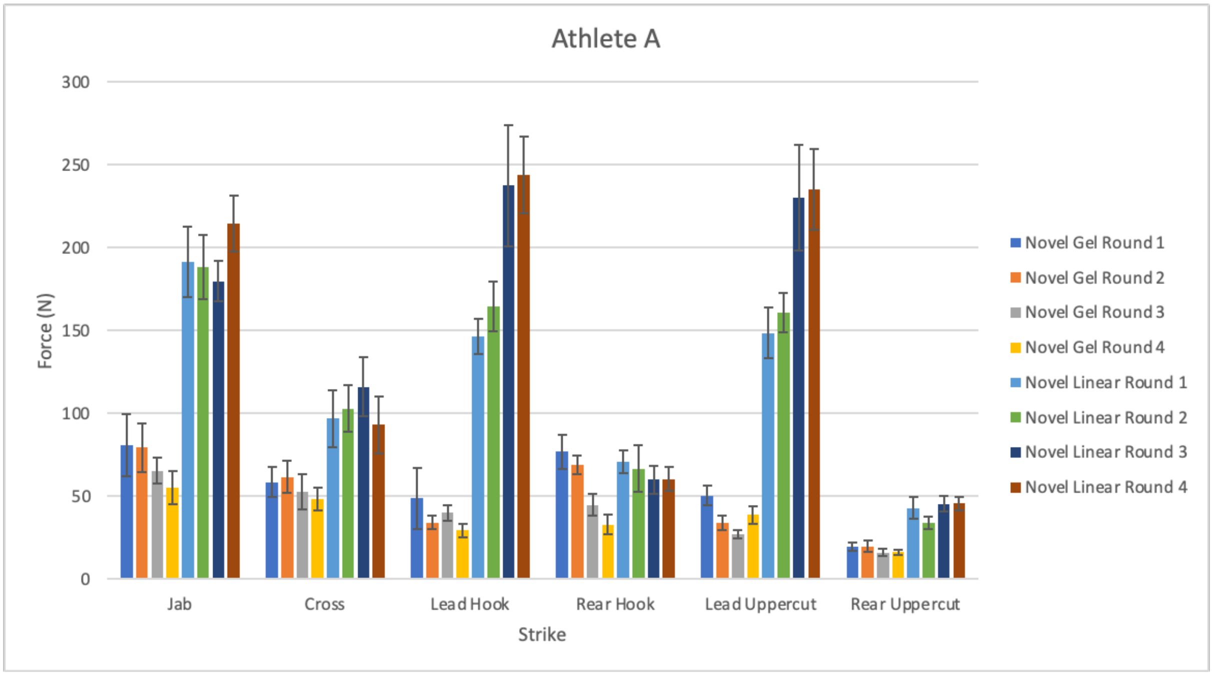

Figure 4.3. Mean force comparisons for impact (Novel) for Athlete A wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

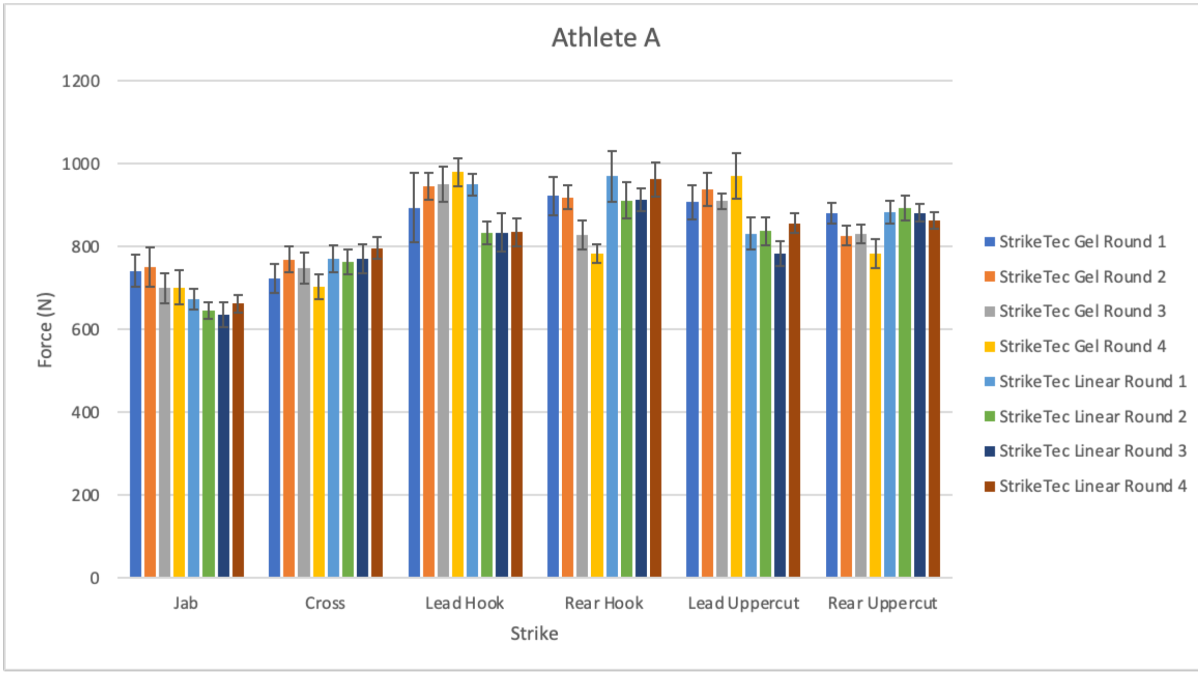

Figure 4.4. Mean force comparisons for effort (StrikeTec) for Athlete A wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

4.3.4B Athlete B

Athlete B was a 26-year-old male with 42 months of recreational boxing experience, orthodox stance, and a self-reported weight of 83.2 kg (Table 4.1). Athlete B had a statistically significant higher value of measured forward effort for the linear hand wraps in the jab ($p = 0.038$), lead hook ($p < 0.0001$) and lead uppercut strikes ($p = 0.0002$; Table 4.6). The sensors did not record values for the right hand, presented as an "X" in Tables 4.6, 4.7 and 4.8. A statistically significantly higher average force was measured by the novel loadpad for the jab with respect to the linear wraps ($p < 0.0001$; Table 4.6, Figure 4.5). A higher overall value was noted for the linear wraps with the lead hook and lead uppercut but this failed to achieve statistical significance ($p = 0.2763$ and $p = 0.2305$, respectively). Given that a statistically significant increase in effort was seen with the linear wraps in all strikes, no definitive conclusions can be made with respect to the higher forces measured by the novel loadpad with the linear wraps. The mean force for each individual 30 second round is demonstrated in Tables 4.7 and 4.8 and presented in Figures 4.6 and 4.7.

Athlete B	StrikeTec Gel Wraps (Mean N (SD))	StrikeTec Linear Wraps (Mean N (SD))	StrikeTec p-value	Novel Gel Wraps (Mean N (SD))	Novel Linear Wraps (Mean N (SD))	Novel p-value
Jab	1041.0 (87.7)	1065.2 (76.9) ^	**0.038 ***	467.7 (301.6)	790.9 (411.1)	**<0.0001 ***
Cross	X	X		X	X	
Lead Hook	1670.6 (233.4)	1934.1 (144.5) ^	**<0.0001 ***	869.7 (653.6)	965.9 (552.3)	0.2763
Rear Hook	X	X		X	X	
Lead Uppercut	1640.0 (212.5)	1744.3 (146.9) ^	**0.0002 ***	569.6 (223.4)	622.1 (360.0)	0.2305
Rear Uppercut	X	X		X	X	

Table 4.6. Mean overall force comparisons for effort (StrikeTec) and impact (Novel) for Athlete B. Values are given in mean Newtons (N) and standard deviation (SD). (^) indicates the higher mean for the StrikeTec force for the gel versus linear wraps. (*) indicates statistical significance at p = 0.05. (X) indicates rounds where data was missing or unable to be collected.

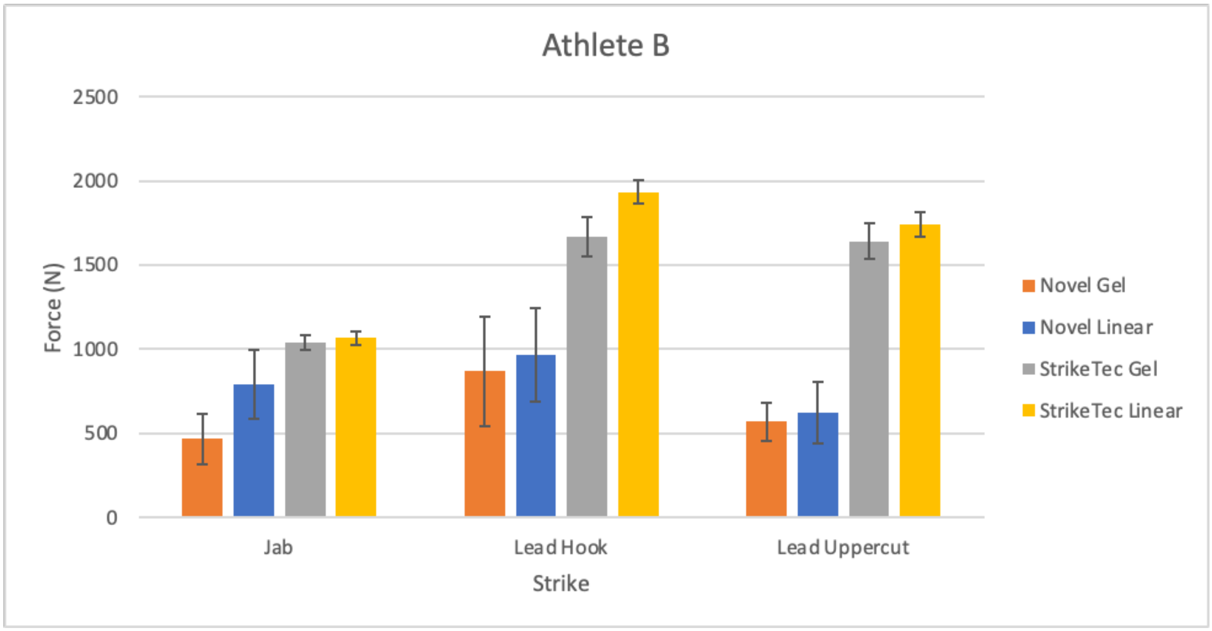

Figure 4.5. Mean overall force comparisons for impact (Novel) and effort (StrikeTec) for Athlete B. Values are presented in mean Newtons (N) and standard deviation (error bars).

Athlete B Linear Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	426.7 (67.7)	24	1106.1 (63.1)	24
	2	437.7 (57.1)	23	1088.3 (84.4)	23
	3	1092.4 (150.9)	24	1026.4 (63.9)	24
	4	1209.5 (353.5)	23	1039.7 (69.1)	23
Cross	1	X		X	
	2	X		X	
	3	X		X	
	4	X		X	
Lead Hook	1	543.9 (75.9)	26	2043.4 (123.7)	26
	2	768.7 (204.2)	21	1937.8 (134.2)	22
	3	1728.3 (240.7)	22	1829.6 (108.1)	23
	4	868.5 (577.9)	17	1910.3 (125.2)	22
Rear Hook	1	X		X	
	2	X		X	
	3	X		X	
	4	X		X	
Lead Uppercut	1	377.5 (49.5)	21	1893.9 (109.7)	21
	2	355.0 (62.2)	24	1720.9 (138.5)	24
	3	650.7 (202.2)	17	1693.3 (93.5)	18
	4	1144.7 (233.2)	20	1661.5 (116.5)	20
Rear Uppercut	1	X		X	
	2	X		X	
	3	X		X	
	4	X		X	

Table 4.7. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete B wearing linear hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD). (X) indicates rounds where data was missing or unable to be collected.

Athlete B Gel Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	383.3 (77.7)	26	1119.2 (82.1)	25
	2	119.0 (51.4)	29	1018.5 (69.0)	29
	3	602.8 (189.8)	27	1039.6 (59.9)	27
	4	730.0 (292.2)	33	1001.4 (90.8)	32
Cross	1	X		X	
	2	X		X	
	3	X		X	
	4	X		X	
Lead Hook	1	1703.4 (668.2)	27	1978.0 (139.7)	27
	2	285.4 (203.0)	28	1660.6 (185.8)	28
	3	809.3 (149.6)	27	1521.3 (132.0)	26
	4	702.4 (374.9)	27	1522.7 (99.0)	28
Rear Hook	1	X		X	
	2	X		X	
	3	X		X	
	4	X		X	
Lead Uppercut	1	500.8 (130.4)	20	1944.5 (132.9)	20
	2	448.0 (278.7)	28	1698.9 (99.9)	28
	3	632.6 (182.1)	26	1505.2 (118.0)	26
	4	690.4 (166.9)	26	1470.8 (117.8)	25
Rear Upper	1	X		X	
	2	X		X	
	3	X		X	
	4	X		X	

Table 4.8. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete B wearing gel hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD). (X) indicates rounds where data was missing or unable to be collected.

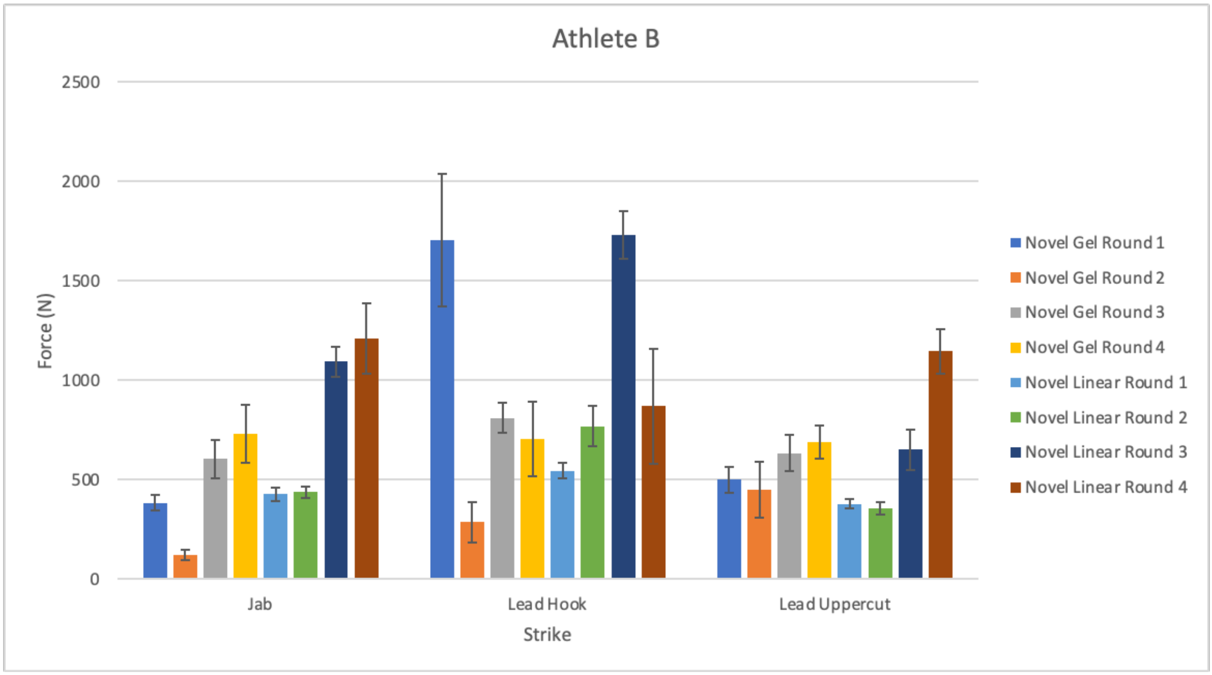

Figure 4.6. Mean force comparisons for impact (Novel) for Athlete B wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

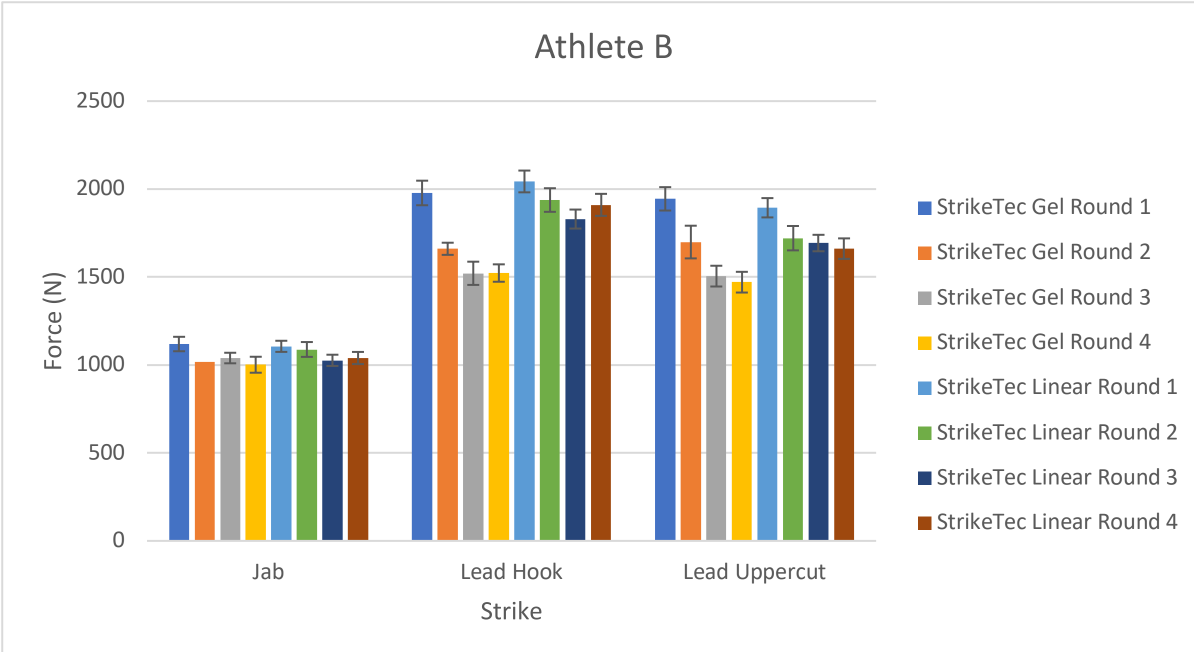

Figure 4.7. Mean force comparisons for effort (StrikeTec) for Athlete B wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

4.3.4C Athlete C

Athlete C was a 20-year-old male with 120 months of recreational/amateur boxing experience, orthodox stance, and a self-reported weight 63.6 kg (Table 4.1). Athlete C had a statistically significant higher value of measured forward effort for the gel hand wraps in the lead hook and for the linear wraps in the cross, rear hook and rear uppercut strikes ($p < 0.001$ for all four strikes; Table 4.9). No statistically significant difference in forward effort was found for the jab or lead uppercut ($p = 0.0641$ and $p = 0.1555$, respectively). A statistically significantly higher force was measured by the novel loadpad in all strikes, with higher measurements found for the linear wraps ($p < 0.0001$ for all comparisons). The mean force for each individual 30 second round is demonstrated in Tables 4.10 and 4.11 and presented in Figures 4.9 and 4.10.

Athlete C	StrikeTec Gel Wraps (Mean N (SD))	StrikeTec Linear Wraps (Mean N (SD))	StrikeTec p-value	Novel Gel Wraps (Mean N (SD))	Novel Linear Wraps (Mean N (SD))	Novel p-value
Jab	707.0 (72.3) ^	687.7 (62.0)	0.0641	85.0 (66.4)	491.1 (84.5)	**<0.0001 ***
Cross	1014.2 (82.9)	1073.4 (101.7) ^	**0.0001 ***	208.0 (246.8)	1824.8 (590.9)	**<0.0001 ***
Lead Hook	1177.9 (98.8) ^	1122.5 (79.6)	**0.0002 ***	48.4 (12.2)	383.3 (60.6)	**<0.0001 ***
Rear Hook	1103.6 (130.2)	1213.3 (109.7) ^	**<0.0001 ***	176.0 (129.3)	1370.8 (577.4)	**<0.0001 ***
Lead Uppercut	958.6 (181.9)	996.0 (98.4) ^	0.1555	74.6 (67.6)	440.3 (60.4)	**<0.0001 ***
Rear Uppercut	920.3 (90.4)	1027.4 (102.9) ^	**<0.0001 ***	152.3 (103.2)	1493.2 (389.7)	**<0.0001 ***

Table 4.9. Mean overall force comparisons for effort (StrikeTec) and impact (Novel) for Athlete C. Values are given in mean Newtons (N) and standard deviation (SD). (^) indicates the higher mean for the StrikeTec force for the gel versus linear wraps. (*) indicates statistical significance at p = 0.05.

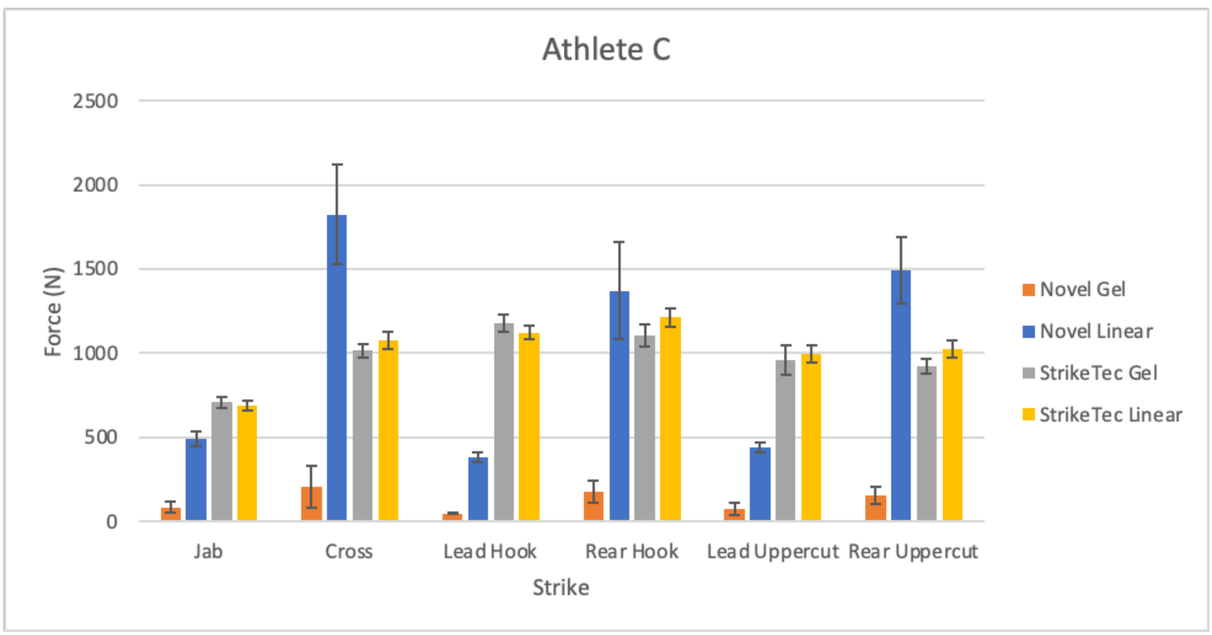

Figure 4.8. Mean overall force comparisons for impact (Novel) and effort (StrikeTec) for Athlete C. Values are presented in mean Newtons (N) and standard deviation (error bars).

Athlete C Linear Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	439.0 (67.9)	23	670.3 (57.0)	22
	2	506.8 (64.6)	22	702.4 (66.2)	22
	3	460.4 (47.1)	21	694.1 (67.3)	20
	4	562.5 (96.4)	21	684.6 (56.8)	21
Cross	1	1135.0 (148.8)	20	987.1 (77.2)	20
	2	2192.4 (492.5)	16	1135.1 (77.1)	16
	3	2220.2 (321.8)	18	1145.4 (83.7)	18
	4	1866.6 (515.9)	19	1044.2 (76.0)	19
Lead Hook	1	371.5 (59.0)	19	1082.8 (56.5)	19
	2	348.6 (45.8)	18	1163.7 (78.4)	18
	3	396.2 (61.9)	19	1135.0 (82.4)	18
	4	415.1 (56.8)	19	1111.1 (81.5)	19
Rear Hook	1	744.0 (80.0)	17	1101.4 (77.1)	18
	2	1012.7 (102.0)	18	1283.8 (85.3)	18
	3	1601.1 (207.6)	18	1282.3 (69.8)	18
	4	2090.9 (423.7)	18	1185.7 (88.4)	18
Lead Upper	1	390.6 (48.4)	16	878.5 (68.5)	16
	2	463.2 (60.2)	15	1034.7 (61.7)	15
	3	434.4 (48.7)	16	1049.2 (92.8)	15
	4	474.5 (50.5)	16	1029.3 (49.3)	15
Rear Uppercut	1	1029.3 (152.1)	17	1006.1 (113.9)	17
	2	1331.7 (151.4)	17	1098.4 (110.5)	17
	3	1803.7 (261.5)	18	1030.5 (89.9(	18
	4	1722.5 (323.2)	22	988.3 (72.2)	23

Table 4.10. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete C wearing linear hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD).

Athlete C Gel Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	198.9 (28.2)	21	721.3 (60.8)	20
	2	50.6 (5.9)	19	711.7 (53.9)	19
	3	46.1 (8.9)	24	686.0 (92.5)	24
	4	50.0 (7.9)	23	712.5 (70.5)	23
Cross	1	44.5 (20.5)	21	1025.1 (56.6)	22
	2	113.8 (21.1)	20	1069.6 (72.3)	20
	3	140.9 (32.6)	16	998.6 (74.5)	18
	4	527.6 (303.0)	20	960.8 (90.6)	20
Lead Hook	1	56.8 (12.4)	17	1114.6 (66.4)	16
	2	44.6 (9.5)	18	1119.8 (91.5)	19
	3	43.6 (12.6)	21	1217.8 (99.1)	21
	4	49.7 (10.3)	21	1241.9 (62.9)	20
Rear Hook	1	197.6 (142.7)	19	1036.2 (100.5)	22
	2	69.8 (16.0)	15	1182.0 (97.3)	18
	3	108.5 (18.9)	12	1159.8 (80.5)	18
	4	308.6 (97.2)	15	1051.3 (166.7)	18
Lead Upper	1	188.7 (34.1)	17	803.8 (101.4)	17
	2	30.2 (4.9)	16	871.6 (112.0)	16
	3	42.1 (9.5)	18	991.2 (143.0)	18
	4	40.7 (8.2)	19	1149.4 (142.8)	18
Rear Upper	1	63.6 (21.8)	19	976.2 (59.6)	20
	2	78.6 (16.4)	17	970.9 (65.2)	19
	3	207.9 (64.2)	15	836.7 (87.8)	19
	4	284.0 (66.8)	16	895.9 (69.3)	20

Table 4.11. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete C wearing gel hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD).

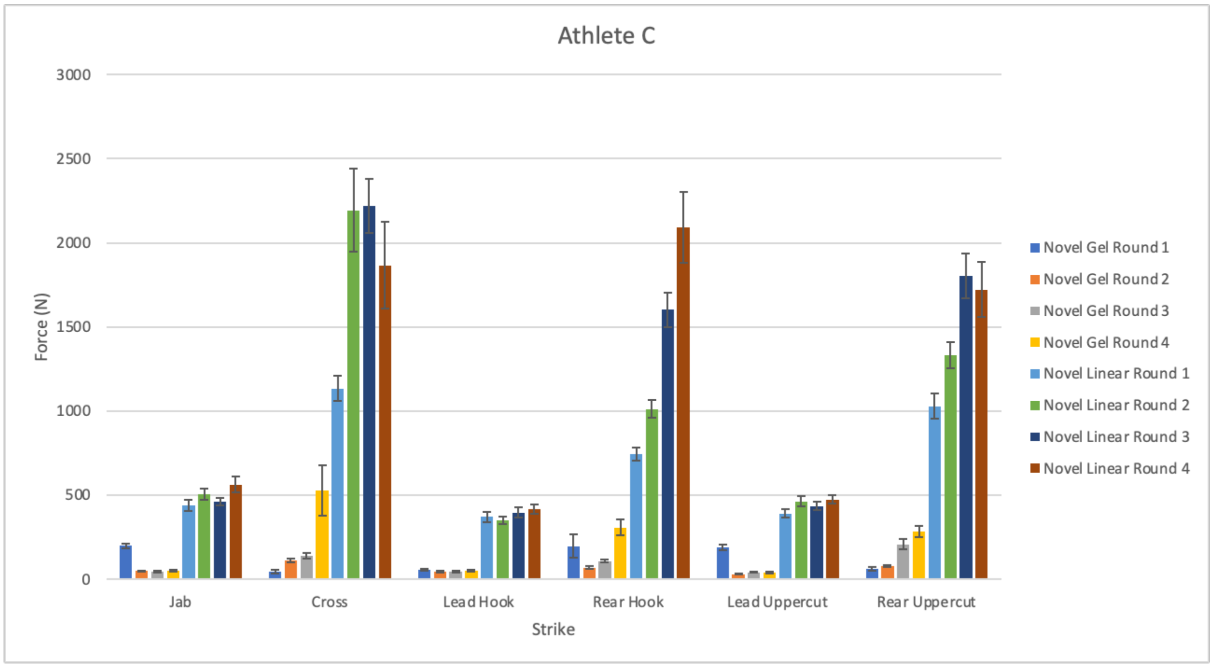

Figure 4.9. Mean force comparisons for impact (Novel) for Athlete C wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

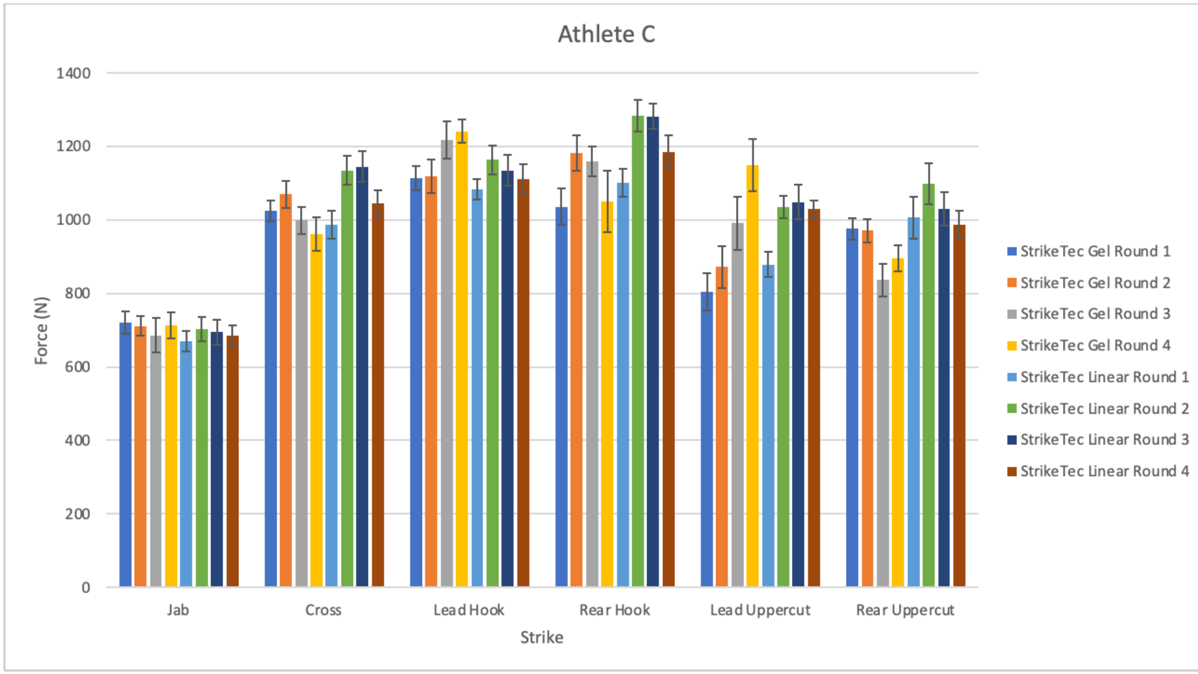

Figure 4.10. Mean force comparisons for effort (StrikeTec) for Athlete C wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

4.3.4D Athlete D

Athlete D was a 27-year-old male with 5 months of recreational boxing experience, orthodox stance, and a self-reported weight 95.5 kg (Table 4.1). Athlete D had a statistically significant higher value of measured forward effort for the gel hand wraps in the jab, rear hook and rear uppercut ($p < 0.002$ for all strikes), and no significant difference found for any of the other strikes (Table 4.12). A statistically significantly higher force was measured by the novel loadpad in all strikes, with higher measurements found for the linear wraps ($p < 0.0001$ for all measurements). The mean force for each individual 30 second round is demonstrated in Tables 4.13 and 4.14 and presented in Figures 4.12 and 4.13.

Athlete D	StrikeTec Gel Wraps (Mean N (SD))	StrikeTec Linear Wraps (Mean N (SD))	StrikeTec p-value	Novel Gel Wraps (Mean N (SD))	Novel Linear Wraps (Mean N (SD))	Novel p-value
Jab	872.2 (118.5) ^	777.9 (95.7)	**<0.0001 ***	442.8 (304.0)	633.4 (161.1)	**<0.0001 ***
Cross	1227.5 (294.8)	1265.9 (115.5) ^	0.2442	82.8 (40.9)	491.7 (87.5)	**<0.0001 ***
Lead Hook	1037.6 (123.3)	1054.1 (128.0) ^	0.3306	379.7 (278.8)	978.6 (329.7)	**<0.0001 ***
Rear Hook	1375.8 (148.7) ^	1308.1 (132.7)	**0.0019 ***	97.4 (63.2)	411.4 (87.3)	**<0.0001 ***
Lead Uppercut	1020.7 (131.6) ^	1015.5 (146.7)	0.7838	377.2 (323.3)	888.9 (319.8)	**<0.0001 ***
Rear Uppercut	1228.4 (136.0) ^	1161.1 (123.2)	**0.0011 ***	63.3 (43.4)	460.0 (95.3)	**<0.0001 ***

Table 4.12. Mean overall force comparisons for effort (StrikeTec) and impact (Novel) for Athlete D. Values are given in mean Newtons (N) and standard deviation (SD). (^) indicates the higher mean for the StrikeTec force for the gel versus linear wraps. (*) indicates statistical significance at p = 0.05.

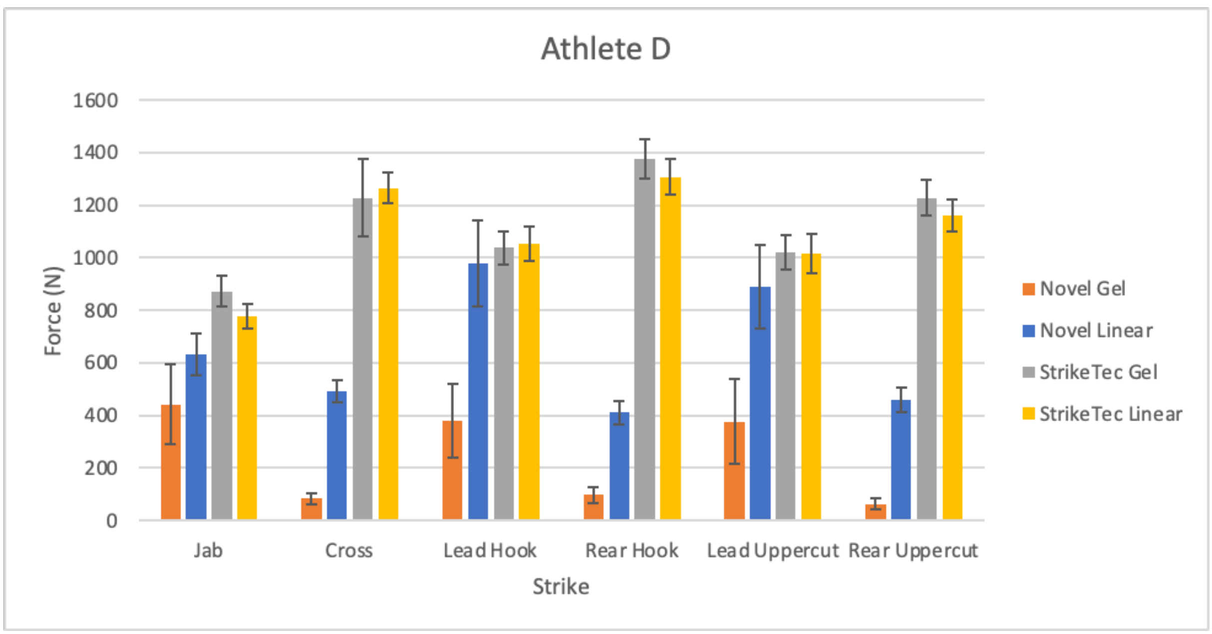

Figure 4.11. Mean overall force comparisons for impact (Novel) and effort (StrikeTec) for Athlete D. Values are presented in mean Newtons (N) and standard deviation (error bars).

Athlete D Linear Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	485.1 (79.2)	36	778.6 (128.8)	29
	2	650.9 (128.9)	33	789.2 (86.7)	33
	3	613.8 (113.9)	31	806.1 (86.6)	31
	4	801.0 (132.8)	32	737.1 (62.2)	31
Cross	1	543.5 (72.5)	26	1265.6 (83.5)	25
	2	521.6 (96.6)	23	1289.4 (112.6)	22
	3	429.2 (66.9)	23	1220.3 (100.7)	24
	4	465.5 (63.4)	23	1290.2 (149.0)	24
Lead Hook	1	695.1 (182.8)	26	1064.8 (142.7)	26
	2	1004.7 (355.0)	34	1094.0 (117.5)	33
	3	1200.7 (283.6)	35	1096.4 (95.1)	35
	4	939.4 (261.4)	33	960.7 (111.7)	33
Rear Hook	1	412.3 (67.9)	25	1300.5 (139.3)	25
	2	403.9 (56.8)	22	1349.8 (147.0)	22
	3	361.1 (62.9)	26	1238.0 (91.3)	26
	4	467.1 (113.6)	26	1350.2 (123.8)	26
Lead Upper	1	681.6 (252.3)	31	1019.8 (108.9)	30
	2	699.3 (220.4)	29	1016.6 (158.3)	28
	3	1050.8 (280.4)	34	1025.5 (187.5)	32
	4	1118.2 (256.5)	28	998.9 (122.3)	29
Rear Upper	1	475.9 (53.8)	24	1211.5 (90.2)	23
	2	440.5 (44.8)	24	1100.5 (124.0)	23
	3	425.7 (68.9)	25	1200.0 (144.2)	25
	4	499.1 (156.7)	24	1131.8 (96.5)	25

Table 4.13. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete D wearing linear hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD).

Athlete D Gel Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	770.6 (232.4)	30	911.7 (92.3)	28
	2	408.3 (223.4)	25	860.6 (132.7)	25
	3	316.9 (257.4)	26	889.1 (105.6)	25
	4	231.6 (151.5)	27	826.2 (128.6)	27
Cross	1	51.5 (18.0)	11	1189.2 (105.4)	17
	2	58.0 (22.9)	17	1305.4 (145.2)	17
	3	66.6 (19.1)	25	1332.0 (136.9)	25
	4	136.1 (25.3)	22	1078.1 (492.6)	22
Lead Hook	1	746.7 (183.9)	25	1009.7 (94.9)	24
	2	290.5 (204.5)	24	1044.4 (140.0)	24
	3	215.3 (87.6)	25	1009.6 (99.6)	25
	4	271.6 (220.8)	27	1082.4 (140.8)	27
Rear Hook	1	51.5 (30.5)	11	1278.7 (169.0)	11
	2	83.1 (60.5)	19	1397.0 (132.9)	19
	3	74.6 (44.3)	22	1451.7 (124.5)	22
	4	152.9 (56.3)	23	1330.2 (138.2)	22
Lead Upper	1	857.1 (279.9)	23	1029.1 (98.4)	23
	2	298.5 (199.0)	25	1001.4 (106.0)	25
	3	245.8 (156.0)	24	940.4 (144.4)	24
	4	173.1 (71.1)	29	1097.0 (123.9)	29
Rear Upper	1	22.9 (9.8)	11	1152.5 (112.1)	12
	2	37.8 (18.1)	14	1366.2 (115.7)	14
	3	45.8 (20.3)	22	1229.5 (128.3)	22
	4	117.4 (27.5)	22	1181.0 (105.3)	22

Table 4.14. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete D wearing gel hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD).

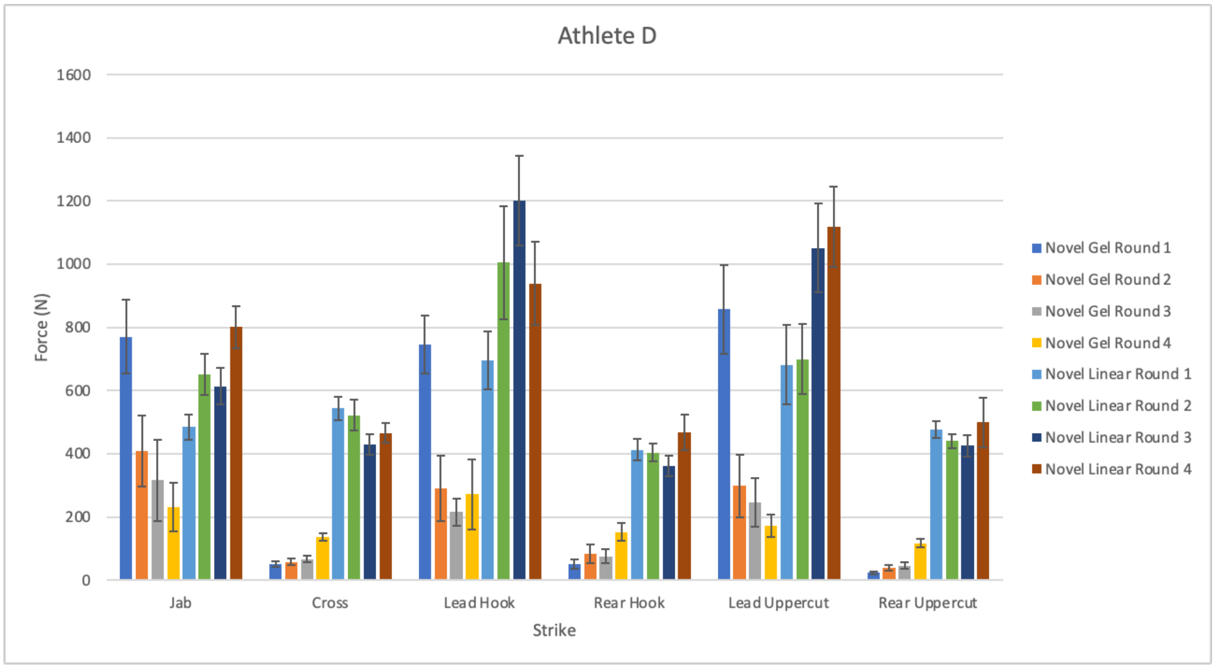

Figure 4.12. Mean force comparisons for impact (Novel) for Athlete D wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

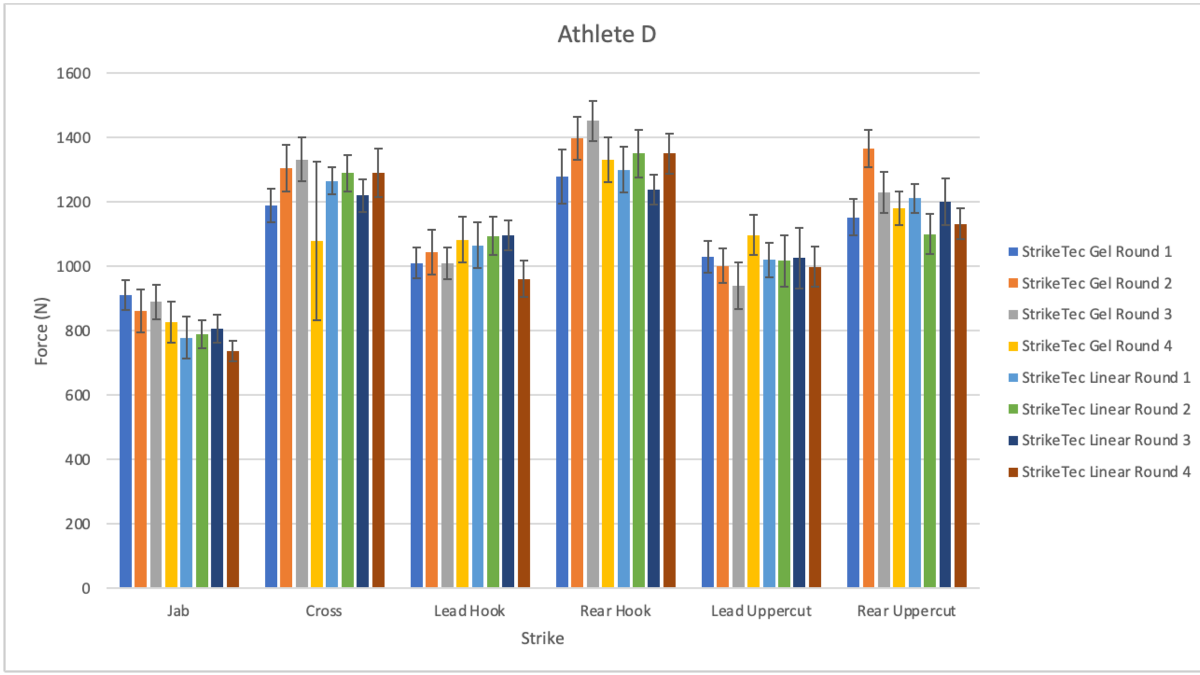

Figure 4.13. Mean force comparisons for effort (StrikeTec) for Athlete D wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

4.3.4E Athlete E

Athlete E was a 40-year-old transfemale with 60 months of recreational boxing experience, orthodox stance, and a self-reported weight 101.4 kg (Table 4.1). Athlete E had a statistically significant higher value of measured forward effort for the gel hand wraps in the jab, lead hook, and lead uppercut strikes ($p < 0.01$ for all strikes), and for the linear wraps in the rear uppercut strike ($p = 0.0415$; Table 4.15). No statistically significant difference in forward effort was found for the cross ($p = 0.1692$) or rear hook ($p = 0.9056$). A statistically significantly higher force was measured by the novel loadpad in all strikes, with higher measurements found for the linear wraps ($p < 0.0001$ for all measurements). The mean force for each individual 30 second round is demonstrated in Tables 4.16 and 4.17 and presented in Figures 4.15 and 4.16.

Athlete E	StrikeTec Gel Wraps (Mean N (SD))	StrikeTec Linear Wraps (Mean N (SD))	StrikeTec p-value	Novel Gel Wraps (Mean N (SD))	Novel Linear Wraps (Mean N (SD))	Novel p-value
Jab	1090.9 (104.2) ^	980.4 (89.7)	**<0.0001 ***	210.2 (69.2)	718.5 (99.6)	**<0.0001 ***
Cross	1493.0 (119.8)	1516.8 (125.0) ^	0.1692	89.0 (27.3)	745.2 (135.1)	**<0.0001 ***
Lead Hook	1763.6 (138.6) ^	1685.5 (180.3)	**0.001 ***	245.7 (116.6)	638.5 (99.5)	**<0.0001 ***
Rear Hook	1782.5 (144.3) ^	1779.9 (160.5)	0.9056	88.2 (25.9)	540.5 (90.4)	**<0.0001 ***
Lead Uppercut	1675.0 (146.5) ^	1599.8 (148.8)	**0.0005 ***	275.4 (56.4)	560.5 (96.3)	**<0.0001 ***
Rear Uppercut	1600.8 (169.6)	1648.8 (145.4) ^	**0.0415 ***	70.7 (20.7)	598.3 (105.6)	**<0.0001 ***

Table 4.15. Mean overall force comparisons for effort (StrikeTec) and impact (Novel) for Athlete E. Values are given in mean Newtons (N) and standard deviation (SD). (^) indicates the higher mean for the StrikeTec force for the gel versus linear wraps. (*) indicates statistical significance at $p = 0.05$.

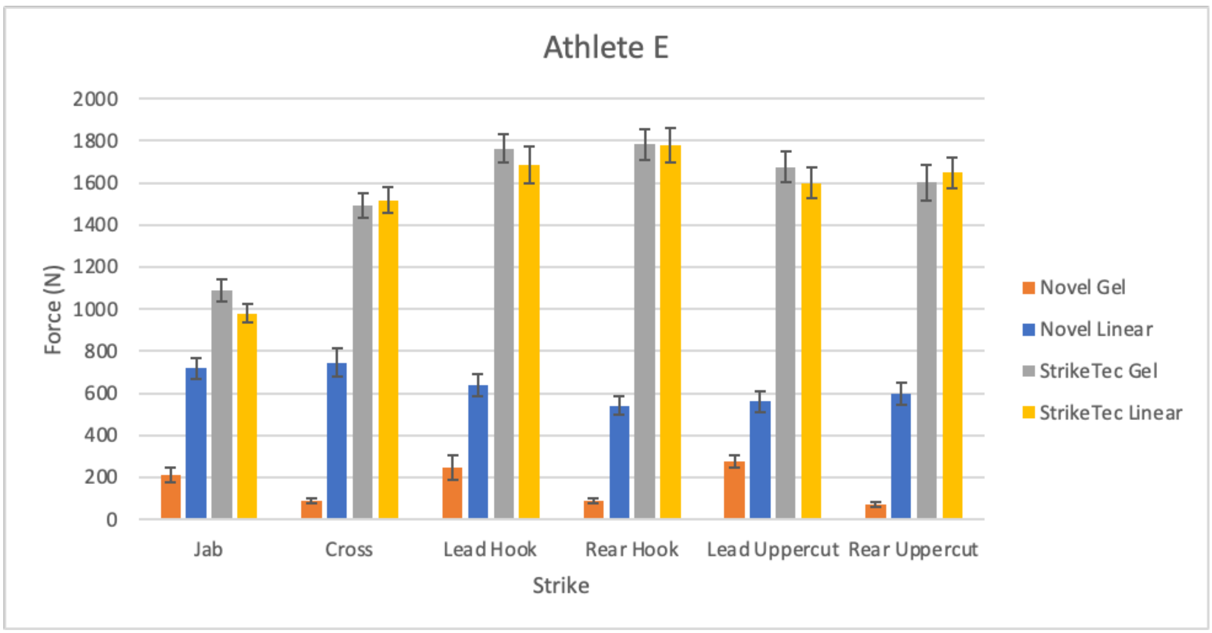

Figure 4.14. Mean overall force comparisons for impact (Novel) and effort (StrikeTec) for Athlete E. Values are presented in mean Newtons (N) and standard deviation (error bars).

Athlete E Linear Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	732.7 (76.2)	24	1003.1 (72.1)	24
	2	666.6 (94.1)	22	984.5 (100.0)	22
	3	663.9 (72.9)	21	980.0 (90.6)	23
	4	796.4 (91.0)	25	955.3 (93.6)	25
Cross	1	677.9 (77.6)	26	1551.1 (116.6)	26
	2	710.6 (70.5)	25	1561.9 (131.2)	25
	3	731.0 (65.5)	25	1444.4 (105.6)	25
	4	**886.5 (200.9)**	**21**	**1507.1 (115.0)**	**21**
Lead Hook	1	549.6 (64.4)	24	1841.6 (155.8)	24
	2	602.4 (69.7)	23	1714.1 (171.6)	23
	3	668.7 (80.3)	25	1594.8 (107.2)	25
	4	734.5 (73.7)	23	1592.7 (160.5)	23
Rear Hook	1	537.0 (91.9)	24	1897.2 (129.4)	24
	2	502.5 (82.1)	24	1822.2 (93.9)	23
	3	520.9 (94.6)	23	1675.8 (147.2)	23
	4	598.4 (65.2)	25	1724.3 (166.7)	25
Lead Upper	1	500.3 (36.4)	23	1741.6 (158.1)	23
	2	501.0 (32.4)	24	1588.9 (120.6)	24
	3	546.6 (67.2)	27	1517.7 (107.1)	27
	4	687.9 (81.6)	25	1568.6 (114.5)	25
Rear Upper	1	545.8 (47.2)	23	1683.6 (98.4)	23
	2	547.5 (85.2)	21	1576.7 (119.8)	20
	3	571.3 (44.9)	17	1654.3 (132.2)	22
	4	725.6 (942)	24	1670.5 (193.9)	24

Table 4.16. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete E wearing linear hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD).

Athlete E Gel Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	225.7 (79.4)	24	1172.4 (112.4)	23
	2	203.5 (69.4)	27	1077.6 (87.8)	27
	3	184.3 (64.9)	24	1053.5 (98.4)	24
	4	231.9 (51.6)	20	1061.4 (73.8)	21
Cross	1	X	X	1568.9 (100.4)	26
	2	91.4 (21.3)	31	1461.0 (81.4)	29
	3	87.6 (33.6)	26	1510.4 (137.6)	27
	4	87.3 (27.8)	22	1424.2 (110.7)	22
Lead Hook	1	280.0 (135.7)	23	1818.2 (119.4)	24
	2	222.8 (100.9)	22	1807.8 (189.9)	22
	3	200.3 (66.6)	26	1716.0 (105.0)	26
	4	284.6 (136.3)	23	1718.2 (101.1)	23
Rear Hook	1	68.5 (14.6)	22	1866.1 (116.8)	23
	2	76.4 (15.6)	27	1739.1 (121.1)	27
	3	88.5 (21.3)	26	1838.1 (146.3)	26
	4	117.4 (20.6)	25	1691.1 (123.8)	24
Lead Upper	1	314.7 (45.4)	16	1759.1 (156.2)	17
	2	267.1 (73.3)	23	1698.8 (120.0)	23
	3	251.7 (46.0)	24	1616.5 (124.8)	25
	4	280.3 (41.7)	27	1656.1 (157.4)	27
Rear Upper	1	63.1 (14.4)	23	1693.2 (232.0)	23
	2	59.1 (14.1)	23	1649.5 (129.3)	23
	3	70.7 (23.0)	24	1499.6 (136.5)	24
	4	88.2 (17.2)	25	1568.3 (90.9)	25

Table 4.17. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete E wearing gel hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD). (X) indicates rounds where data was missing or unable to be collected.

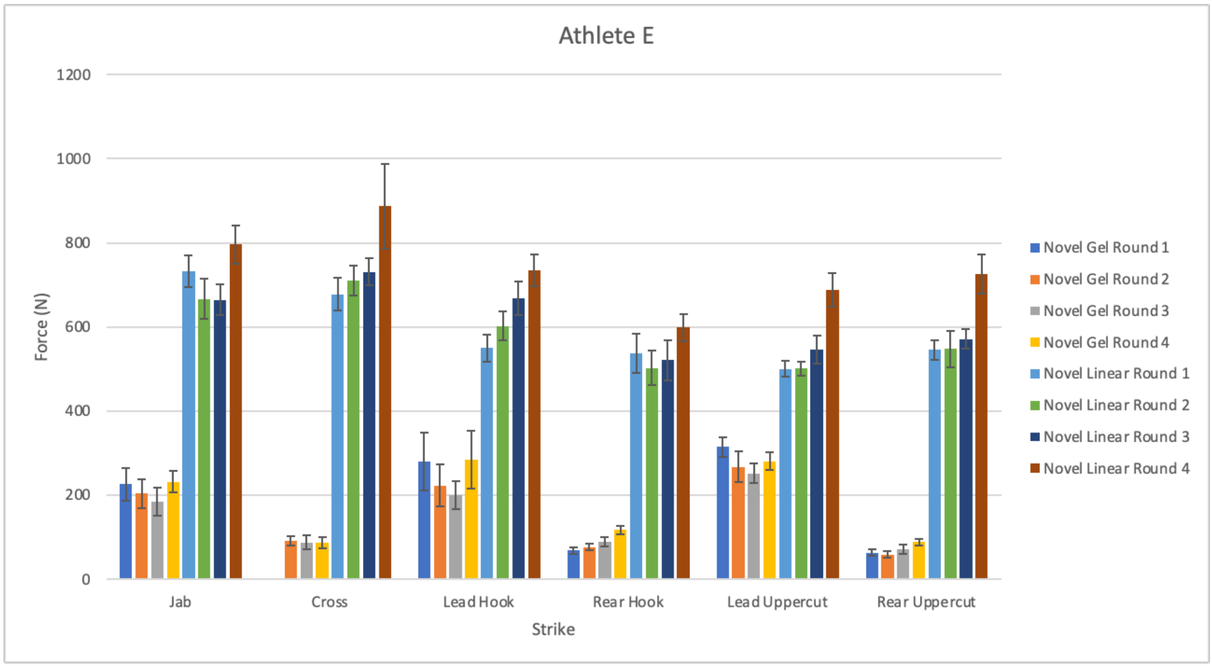

Figure 4.15. Mean force comparisons for impact (Novel) for Athlete E wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

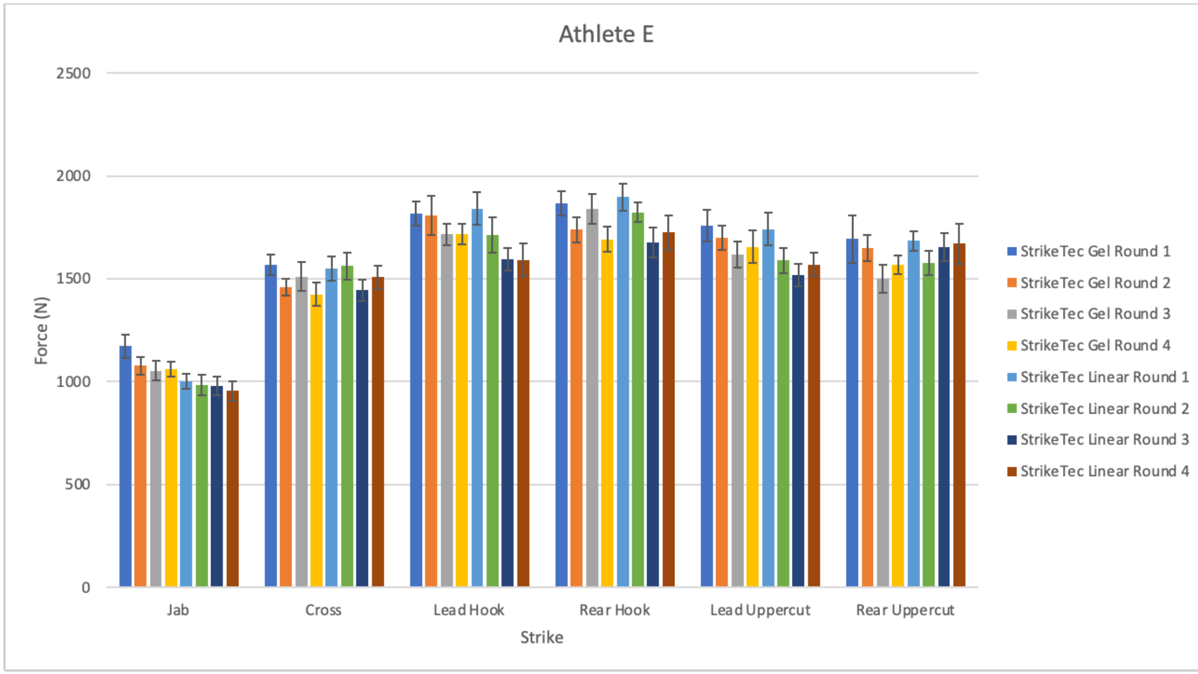

Figure 4.16. Mean force comparisons for effort (StrikeTec) for Athlete E wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

4.3.4F Athlete F

Athlete F was a 40-year-old male with 177 months of recreational/amateur Muay Thai experience, orthodox stance, and a self-reported weight 72.7 kg (Table 4.1). Athlete F had a statistically significant higher value of measured forward effort for the gel hand wraps in the cross strike, and for the linear wraps in the lead hook and lead uppercut strikes ($p < 0.001$ for all three strikes; Table 4.18). No statistically significant difference in forward effort was found for the jab, rear hook or rear uppercut. A statistically significantly higher force was measured by the novel loadpad in all strikes ($p < 0.0001$) except for the lead hook, with higher measurements found for the linear wraps. Despite not achieving statistical significance (p – 0.382), the lead hook also had a higher measured impact force for the linear wraps, although the absolute difference was small (51.3 N). The mean force for each individual 30 second round is demonstrated in Tables 4.19 and 4.20 and presented in Figures 4.18 and 4.19.

Athlete F	StrikeTec Gel Wraps (Mean N (SD))	StrikeTec Linear Wraps (Mean N (SD))	StrikeTec p-value	Novel Gel Wraps (Mean N (SD))	Novel Linear Wraps (Mean N (SD))	Novel p-value
Jab	752.1 (81.8) ^	726.2 (94.6)	0.0752	193.9 (73.5)	783.5 (352.8)	**<0.0001 ***
Cross	1104.4 (85.3) ^	1012.9 (66.8)	**<0.0001 ***	123.6 (50.8)	494.7 (76.5)	**<0.0001 ***
Lead Hook	1099.4 (170.2)	1218.6 (147.0) ^	**0.0007 ***	383.3 (336.5)	434.6 (125.7)	0.382
Rear Hook	1226.0 (107.9) ^	1199.2 (111.7)	0.1927	135.6 (57.9)	473.0 (90.4)	**<0.0001 ***
Lead Uppercut	1143.0 (151.8)	1226.8 (88.7) ^	**0.0011 ***	262.8 (192.4)	669.5 (314.9)	**<0.0001 ***
Rear Uppercut	1200.3 (133.1) ^	1183.4 (101.7)	0.4655	78.0 (44.0)	337.3 (57.2)	**<0.0001 ***

Table 4.18. Mean overall force comparisons for effort (StrikeTec) and impact (Novel) for Athlete F. Values are given in mean Newtons (N) and standard deviation (SD). (^) indicates the higher mean for the StrikeTec force for the gel versus linear wraps. (*) indicates statistical significance at p = 0.05.

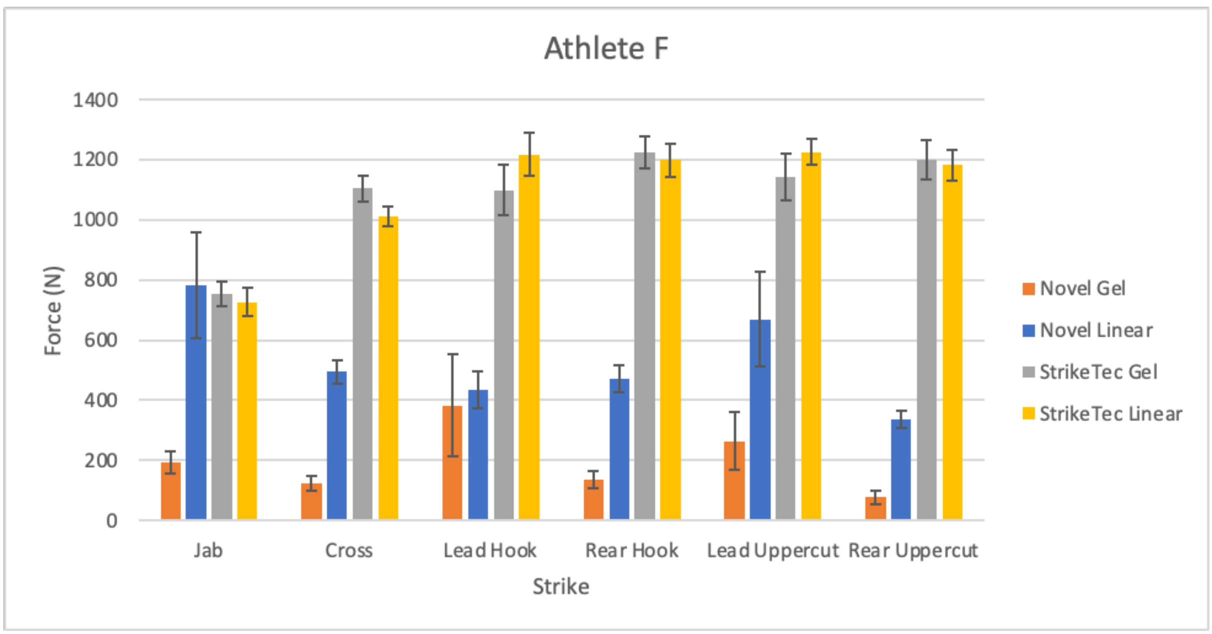

Figure 4.17. Mean overall force comparisons for impact (Novel) and effort (StrikeTec) for Athlete F. Values are presented in mean Newtons (N) and standard deviation (error bars).

Athlete F Linear Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	581.3 (123.8)	21	724.7 (47.4)	12
	2	1081.5 (396.9)	25	730.8 (117.1)	25
	3	644.1 (196.7)	23	721.8 (88.5)	22
	4	X	X	X	X
Cross	1	486.5 (119.4)	10	1024.0 (74.6)	10
	2	550.9 (67.0)	15	1044.7 (59.9)	15
	3	481.5 (41.6)	13	1029.6 (45.7)	13
	4	458.0 (41.7)	16	962.5 (58.0)	16
Lead Hook	1	408.8 (118.6)	18	1210.2 (121.6)	18
	2	460.3 (130.6)	18	1227.0 (171.9)	18
	3	X	X	X	X
	4	X	X	X	X
Rear Hook	1	454.4 (95.5)	13	1255.8 (100.6)	13
	2	491.7 (111.6	16	1215.7 (98.0)	17
	3	459.2 (86.9)	18	1178.5 (127.5)	18
	4	484.3 (68.4)	17	1161.2 (102.7)	17
Lead Upper	1	550.7 (133.4)	15	1246.1 (103.7)	15
	2	956.5 (350.6)	17	1247.9 (86.3)	17
	3	463.1 (81.7)	15	1183.5 (60.4)	15
	4	X	X	X	X
Rear Upper	1	319.6 (36.5)	12	1133.6 (139.2)	12
	2	317.1 (43.7)	14	1212.5 (77.5)	14
	3	373.3 (56.3)	15	1224.7 (79.5)	15
	4	334.4 (69.5)	15	1154.8 (88.6)	15

Table 4.19. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete F wearing linear hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD). (X) indicates rounds where data was missing or unable to be collected.

Athlete F Gel Wraps	Round	Novel Loadpad Force (Mean N (SD))	Novel strike count (n)	Striketec Force (Mean N (SD))	Striketec strike count (n)
Jab	1	141.7 (27.4)	19	795.1 (49.9)	19
	2	176.8 (54.8)	22	794.5 (61.0)	21
	3	173.9 (66.6)	30	714.2 (89.3)	30
	4	275.9 (55.7)	24	727.4 (78.3)	23
Cross	1	68.1 (30.8)	9	1071.0 (93.6)	9
	2	111.3 (34.5)	11	1148.5 (65.4)	10
	3	149.8 (34.8)	11	1102.8 (72.8)	11
	4	155.2 (51.2)	11	1093.0 (99.2)	11
Lead Hook	1	163.8 (59.4)	13	1175.4 (170.3)	13
	2	224.3 (80.4)	17	1168.3 (130.2)	17
	3	351.1 (167.4)	16	1048.9 (190.8)	16
	4	720.7 (450.2)	18	1015.0 (139.5)	16
Rear Hook	1	121.9 (82.4)	10	1295.3 (97.3)	10
	2	141.9 (57.9)	11	1291.3 (83.7)	10
	3	135.9 (53.1)	15	1184.1 (87.4)	15
	4	139.3 (48.7)	17	1183.8 (109.3)	17
Lead Upper	1	128.5 (36.0)	15	1109.4 (95.6)	15
	2	173.0 (120.5)	15	1022.8 (107.1)	14
	3	226.7 (57.5)	16	1091.5 (92.8)	16
	4	509.0 (200.6)	16	1331.1 (99.4)	16
Rear Upper	1	57.7 (16.2)	13	1141.1 (66.5)	13
	2	53.2 (27.0)	11	1348.7 (156.5)	10
	3	79.6 (51.1)	12	1195.8 (125.9)	12
	4	117.6 (41.9)	13	1149.4 (84.3)	13

Table 4.20. Mean force comparisons for effort (StrikeTec) and impact (Novel) for Athlete F wearing gel hand wraps per 30 second round. Values are given in mean Newtons (N) and standard deviation (SD).

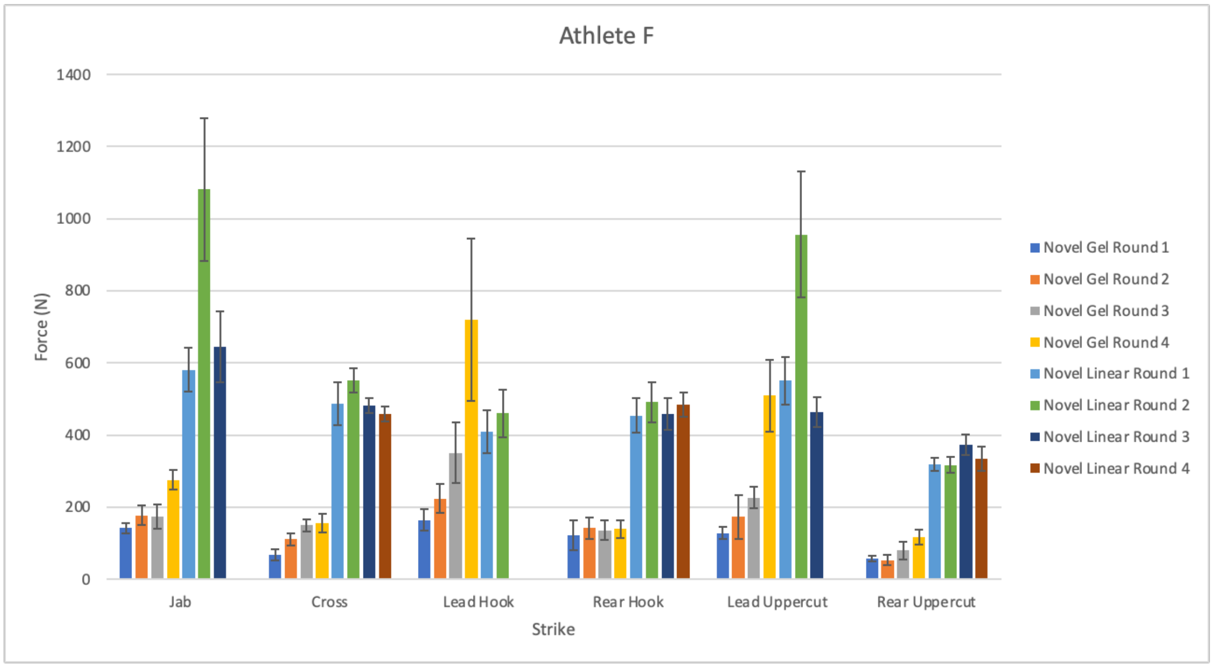

Figure 4.18. Mean force comparisons for impact (Novel) for Athlete F wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

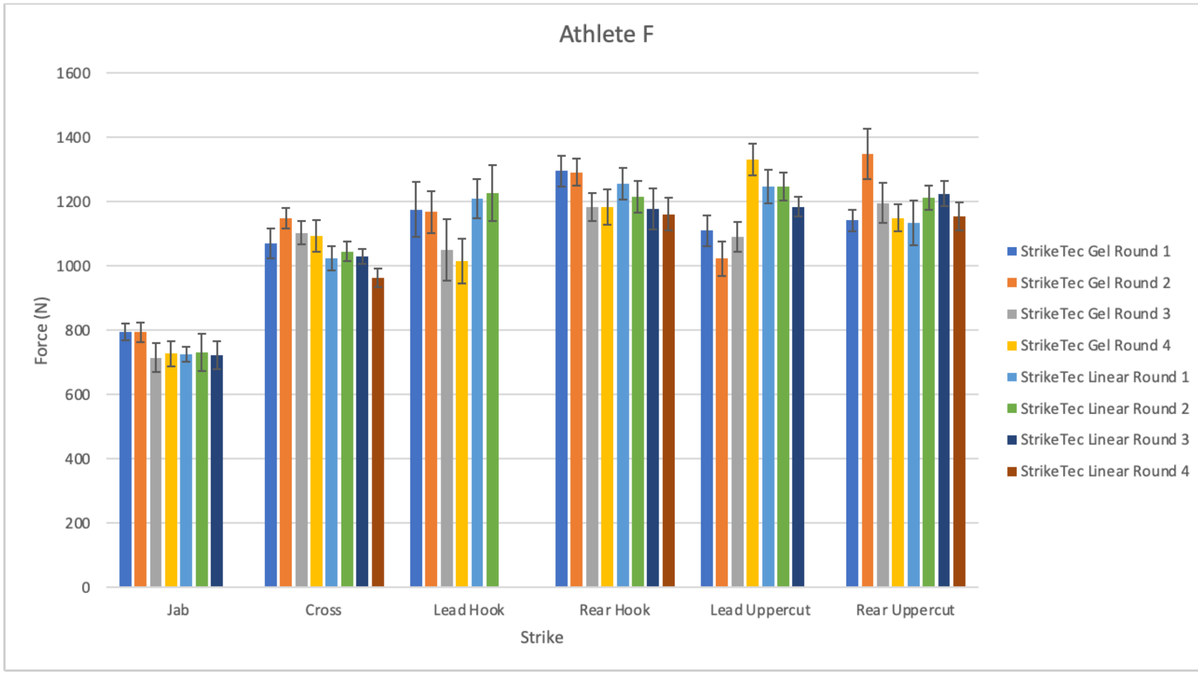

Figure 4.19. Mean force comparisons for effort (StrikeTec) for Athlete F wearing gel or linear hand wraps per 30 second round. Values are presented in mean Newtons (N) and standard deviation (error bars).

4.4 Discussion

The investigations of protective gear in combat athletes have largely investigated the amount of forward force and/or impact load that can be generated against an opponent. This is an understandable safety measure as during competitions and sanctioned fights, the potential for significant head and neck injury can have fatal consequences. However, for most combat sport athletes who do not participate in matches, competition or sparring, the focus of injury prevention is better targeted at the level of the hand and wrist as this will affect change at all levels of experience and participation.

The use of static load cells to measure forward force generation by combat athletes provides an easy mechanism for measurements. The ability to measure retrograde forces experienced by the hand and wrist is a much more complex and difficult task. Additionally, the movements of the hand during striking can significantly alter the effects of how force is transmitted to the hand and wrist. Static testing using stiff models is therefore insufficient to allow adequate force measurements. Using the verified novel loadpad sensor herein we have developed a technique and protocol to measure retrograde force experienced by the hand and wrist in a realistic and dynamic striking setting.

In all measurements performed in the 6 combat athletes involved in this study, the novel loadpad detected a higher level of force at the hand/wrap interface while the athlete was wearing the linear wraps compared to the gel wraps. In the scenarios where effort level (as measured by the StrikeTec accelerometers) was statistically significantly higher in the linear wraps, no definitive conclusions can be drawn as to the degree of energy absorption of the different types of hand wraps. However, given that the force load with the linear wraps was consistently higher in all athletes, this leads to the conclusion that the linear wraps are less efficient at energy absorption at the hand/wrap interface compared to the gel wraps. Additionally, if the potential error rate is assumed to be near a maximum of 18.9% for the linear wraps and 9.1% for the gel wraps as seen in the sensor validation results in Chapter 3, nearly all of the above differences between the means remains substantially different. In circumstances where there was no significant difference between the two wrap subtypes, this may be due to improper technique wherein the glove strikes the bag along the palmar portion of the glove and distal phalanges rather than perpendicular over the proximal phalanges and MCP joints.

Although the small number of athletes precludes any statistical analysis, some other generalizable trends were noted in the datasets presented above. It was noted that the athletes with the higher experience level (Athletes C, E and F) had the highest differences between the linear and gel wraps detected by the novel loadpad, but not necessarily the highest level of measured forward effort on the StrikeTec accelerometers. This trend echoes previous studies looking at forward velocity and subsequent bag momentum or effective mass during striking by athletes of various skill levels.(45, 119) Results in these studies demonstrated that skill/experience level did not result in a difference in forward velocity during striking, but athletes of a higher skill level were better able to impart momentum to a heavy bag or target, most likely due to improved technique.

Additionally of interest is the finding that during progressive rounds, a sequential increase in the impact forces was noted with the linear but not the gel wraps in the athletes. This occurred despite no apparent increase in overall forward effort. This trend could be due to 1) cumulative compression of the glove padding and/or 2) subtle tightening or loosening of the linear wraps over consecutive strikes. A study performed by Smith (1987) looked at force transmission during a series of consecutive strikes with boxing gloves and found that after 50 consecutive strikes the force impact rose by 118%.(120) Although the contents of boxing glove padding has changed since this publication, a more recent study by Lee et al. (2014) also demonstrated an increase in force during the early phases of consecutive strikes with boxing gloves.(115) It is reasonable to assume that the compression of the boxing glove padding could also result in an increase in the forces at the hand/wrap interface. However, as this trend was not noted with the use of the gel wraps, the major contributing factor is more likely related to the linear wraps rather than to the gloves.

Limitations to this study are related to the equipment that was used, as the findings are therefore limited to this specific equipment. Only one type of gel wrap, linear wrap and boxing glove were used in this study, and there is a wide variety of commercially available wraps and gloves that vary in composition. Additionally, an Aquabag was chosen for measurements as the teardrop shape allows for easier perpendicular impact for all 6 strikes, but in theory limits the findings to this specific heavy bag which has different elastic and deformation characteristics than a traditional cylindrical heavy bag. However, given the level of difference seen in our measurements between the two wrap subtypes, this theoretical limitation based on impact surface is unlikely to have a real-life effect. Limitations secondary to the load cell used may also have had an influence on study measurements, as the novel loadpad is a cumulative load cell without impact or pressure mapping. Impact surface area will therefore have an influence on gross force measurements and anticipated force transmission to the hand and would most likely be related to athlete technique. As all participants were compared to themselves, the assumption is that an individual's technique would not change between the wrap types and should therefore remain directly comparable.

Taken together, these results demonstrate that the gel wraps provide improved force absorption at the hand/wrap interface as compared to the linear wraps. This trend was observed regardless of athlete weight class, age or sex, but is especially true of higher experience level. Although the number of strikes for each individual athlete was high, the total number of athletes was low and only generalizations can be made about sub-groups. This opens an avenue for future research to include more athletes in a similar study to further define these trends into usable recommendations for hand protection in combat athletes.

Chapter 5. Paper survey

Eva M. Gusnowski, Daniel Langohr, Kenneth Faber and Ruby Grewal

5.1 Introduction

The use of protective gear in athletes has undergone significant evolution in many sports, including combat athletes. However, regardless of the potential for injury, there are often either knowledge gaps or unenforced rules and regulations about its regular use. Additionally, with the significant amount of commercially available gear, the choices that athletes make can often be based on familiarity and ease of use rather than on evidence-based and objective measures of protection. The purpose of this survey was to determine the type of hand wraps that combat athletes preferred to use before and after the striking study in Section 4 above.

5.2 Materials and methods

Prior to participation in the force analysis (Section 4), all participating athletes were asked to complete a paper survey (Appendix C). The survey collected information on demographic data (Table 4.1) as well as previous hand/wrist injury. Participants were also asked to choose their preferred type of hand wrap before testing commenced. Athletes that completed the second day of testing were asked to complete a final section regarding which hand wrap they believed performed better at protecting their hands from impact, and which wrap they would use after completing the study.

5.3 Results

Table 5.1 shows the results of the paper survey (refer to Table 4.1 for athlete demographics). Only two of the athletes (Athlete B and Athlete D) had a history of a known remote upper extremity injury. None of the athletes had an acute or subacute injury. All 6 of the athletes routinely used linear wraps prior to participating in the study. After completing both days of the study protocol, 5/6 (83.3%) of the athletes subjectively felt that the gel wraps performed better during the study and provided better force absorption. One athlete (Athlete D) felt that the linear wraps performed better during the study. Five of the six athletes (83.3%) stated that they would prefer to continue to use linear wraps, and one athlete (1/6; 16.7%) stated that they would like to use gel wraps following completion of the study protocol.

Athlete	History of hand/wrist injury	Wraps used pre-study	Better wrap performance during study	Wraps used post-study
A	None	Linear	Gel	Gel
B	Non-specified fracture right hand 2011	Linear	Gel	Linear
C	None	Linear	Gel	Linear
D	Left wrist strain 10 years prior	Linear	Linear	Linear
E	None	Linear	Gel	Linear
F	None	Linear	Gel	Linear

Table 5.1. Pre- and post-testing survey results for preferred hand wrap in athletes that completed both days of the study.

5.4 Discussion

An athlete's choice of hand wrap is generally based on availability, comfort and experience. This is influenced by coaches and trainers that will impart and perform a certain method of hand wrapping on their athletes and students. The benefit of hand protection has been widely demonstrated, and not only provides impact absorption but also stability to the hand and wrist and improved fit within a glove.

Our results demonstrate that perceived performance does not necessarily dictate the continued use of a product. This is in keeping with a review looking at athletes' and coaches' perceptions, recommendations and use of headgear for concussion prevention.(121) In this scoping review the authors demonstrated that the majority of athletes and coaches believed that headgear was important for concussion prevention, however few used it routinely unless it's use was enforced or absolutely required. All six athletes that completed the study protocol used linear wraps before the study, with five athletes believing that the gel wraps provided better protection and performed better during the study. Despite this finding, four of these athletes stated that they would continue to use linear wraps even though they felt they performed more poorly in the study. This is likely because the linear wraps provide not only familiarity but also customizability for padding and compression, whereas most gel wraps are available in only pre-fabricated sizes.

This study is limited by the small number of participants and no statistical analyses could be reasonably performed. However, the data demonstrates a trend towards athletes continuing with their original wrap choice. It would therefore be of benefit to perform further surveys in combat athletes to determine the factors underlying their wrap choice to dictate future wrap designs that provide ease of use, comfort and the highest level of protection.

Chapter 6. Innovation and future directions

6.1 Future studies

The benefits of hand protection have been demonstrated in a multitude of studies in combat athletes. Hand protection not only prevents injury to an opponent, but also provides a significant reduction in injuries to the athlete performing the strike. Several studies have looked into the properties of various weights and composition of gloves, however, there have been no studies looking at the differences and benefits of various types of hand wraps. This innovative study provides a comparative baseline for the protective capabilities of two commonly used and commercially available types of hand wraps.

Further studies looking at the impact force at the hand/wrap interface could improve and expand upon the current study design. The use of a pressure sensor that provides a topographical map of impact force and location would offer important information about the biomechanics of an athlete's punch in addition to overall force measurements. This technology could be used to test innovative hand wrap designs as well as different methods of hand wrapping. Additionally, traditional hand wraps for sanctioned competitions are comprised of a stiff gauze construct which has undergone little evolution. Pressure sensors such as the one described could also investigate the protective capabilities of these constructs and provide information on how to better enhance injury prevention in the ring as well as the gym. Sensors that provide topographical maps could also be applied to training, providing athletes with immediate feedback during striking. This could be extended along the spectrum of athlete experience, from recreational to professional, to aid in skill enhancement and the teaching of appropriate striking biomechanics.

6.2 Hand wrap innovation and idealized design

No studies have investigated how hand wraps provide protection against injury during striking. Two theorized aspects of hand wraps should be considered: 1) force absorption and dissipation and 2) joint stability. Force absorption and dissipation is an important aspect of the hand wrap as direct and repeated impact along the MCPs and proximal phalanges risks not only acute injury, but also cumulative chronic injuries. This was demonstrated by the high volume of these injuries reported in striking sports in the systematic review presented in Section 2. Joint stability is a difficult task given the multiple articulations and complex motions of the fingers, hand and wrist. A hand wrap should provide sufficient stability to tension the deep transverse metacarpal ligaments and partially immobilize the mobile ulnar hand while still allowing a fist to be made, which by necessity requires some palmar deviation of the ring and small finger metacarpals. Additionally, the carpal bones should be partially immobilized to maintain flexion/extension neutrality and allow energy to be propagated along the forearm, but still allow some element of ulnar and radial deviation and flexibility for combat athletes that participate in grappling, wrestling and alternative striking. Important elements for an innovative hand wrap design should therefore provide impact absorption as well as flexible stability to the hand and wrist.

With respect to force absorption, the material incorporated into the wrap should be cautiously considered. High density materials tend to absorb more energy, but depending on the cellular structure and other composition factors, the properties of the material will dictate whether it is useful in an athletic setting. Many combat athletes have innovated ways to enhance padding over the MCP joints, including multiple layers of material added over the MCPs/proximal phalanges. Other commercially available wrap designs include the interposition of various densities of foam rods into the wraps (Radius Wraps, Fumetsu Combat, Buckingham, England), or attached to the end of traditional linear wraps (Knuckle Guards, BOXRAW, Coventry, England). This, however, can make for increased bulk, making glove placement over the wraps difficult and uncomfortable. Additionally, the compression of foam after only a minimal number of strikes, as seen in gloves with foam padding,(119) may preclude its use as an ideal shock absorber in a hand wrap setting. Section 4 above demonstrates that the gel material used in the two tested wraps provides superior force absorption to a standardized linear wrap. The use of gel material as an impact absorption element in an ideal hand wrap design would therefore objectively enhance hand/wrist protection versus wrap material alone. This piece of gel could be modelled to conform along the dorsal surface of the individual MCP and proximal phalanges rather than existing as a single block. This would allow the inclusion of a wrap portion that could then be comfortably wrapped between the web spaces to tension the deep transverse metacarpal ligaments and wrap around the wrist to provide appropriate and customized joint stability.

6.3 Closing remarks

Most protective equipment for combat sports has not been adequately tested to support claims of increased support and injury prevention. Herein we have described and conducted a study to quantify the location and type of hand and wrist injuries sustained by combat athletes, and to directly assess whether there is an identifiable difference between commercially available protective hand gear for use in combat sports. The results presented can inform athletes with evidence-based recommendations on effective hand protection. Additionally, this study has provided a baseline and platform for future testing of innovative hand wrap designs. This will allow us to provide maximum protection against potentially disabling hand and wrist injury in combat sport athletes.

Bibliography

1. Iole K. UFC's TV ratings amid COVID-19 pandemic a sign of growing fan interest: Yahoo! News; 2020 [Available from: https://ca.news.yahoo.com/ufc-tv-ratings-amid-covid-19-pandemic-a-sign-of-growing-fan-interest-170931619.html.
2. Hoke M, Omar NB, Amburgy JW, Self DM, Schnell A, Morgan S, et al. Impact of exercise on bone mineral density, fall prevention, and vertebral fragility fractures in postmenopausal osteoporotic women. J Clin Neurosci. 2020;76:261-3.
3. Hackney ME, Wolf SL. Impact of Tai Chi Chu'an practice on balance and mobility in older adults: an integrative review of 20 years of research. J Geriatr Phys Ther. 2014;37(3):127-35.
4. Bolanowski MS, A., Bolanowski, J., Pluskiewicz, W., Adamczyk, P. . Beneficial effects of tai chi on women's skeletal status assessed by quantitative ultrasound at the hand phalanges - one-year follow-up study. Advances in Clinical and Experimental Medicine. 2007;16(5):675-81.
5. Borba-Pinheiro CJ, Dantas EHM, Jesus FPd, Rocha-Júnior ORB, Drigo AJ, Carvalho MCGdA, et al. Adapted karate training on functional autonomy, muscle strength and quality of life of elderly man with osteoporosis: a clinical case. Archives of Budo Science of Martial Arts and Extreme Sports. 2016;12:71-6.
6. Ryan W.T. Lip, Fong SSM, Ng SSM, Liu KPY, Guo X. Effects of Ving Tsun Chinese martial art training on musculoskeletal health, balance performance, and self-efficacy in community-dwelling older adults. J Phys Ther Sci. 2015;27:667-72.
7. van der Zijden AM, Groen BE, Tanck E, Nienhuis B, Verdonschot N, Weerdesteyn V. Can martial arts techniques reduce fall severity? An in vivo study of femoral loading configurations in sideways falls. J Biomech. 2012;45(9):1650-5.
8. Barbeta CJdO, Krahenbühl T, Gonçalves EM, Guerra-Júnior G. Effects of Combat Sports on Bone Mass: Systematic Review. Revista Brasileira de Medicina do Esporte. 2019;25(3):240-4.
9. Mariona A. Violan EWS, Merrilee N. Zetaruk,, Micheli LJ. The Effect of Karate Training on Flexibility, Muscle Strength, and Balance in 8- to 13-Year-Old Boys. Pediatric Exercise Science. 1997;9:55-64.
10. Young Ho S, Hyun Lyung J, Ho Youl K. Effects of Taekwondo Training on Bone Mineral Density of High School Girls in Korea. Biology of Sport. 2011;28(3):195-8.
11. Baudry S, Roux P. Specific Circuit Training in Young Judokas. Research Quarterly for Exercise and Sport. 2009;80(2):146-52.
12. Damir Sekulic SK, Ratko Katic,, Ostojic L. Judo Training is More Effective for Fitness Development Than Recreational Sports for 7-Year-Old Boys. Pediatric Exercise Science. 2006;18:329-38.
13. Szabo A, Urbán F. DO COMBAT SPORTS DEVELOP EMOTIONAL INTELLIGENCE? Kinesiology. 2014;46(1):53-60.
14. Kotarska K, Nowak L, Szark-Eckardt M, Nowak M. Selected Healthy Behaviors and Quality of Life in People Who Practice Combat Sports and Martial Arts. International Journal of Environmental Research and Public Health. 2019;16(5):875.
15. Hojjat H, Svider PF, Lin HS, Folbe AJ, Shkoukani MA, Eloy JA, et al. Adding Injury to Insult: A National Analysis of Combat Sport-Related Facial Injury. Ann Otol Rhinol Laryngol. 2016;125(8):652-9.
16. Tommasone BA, Valovich McLeod TC. Contact sport concussion incidence. J Athl Train. 2006;41(4):470-2.
17. Boxing Participation by Children and Adolescents. PEDIATRICS. 2011;128(3):617-23.
18. Miele VJ, Bailes JE, Cantu RC, Rabb CH. Subdural hematomas in boxing: the spectrum of consequences. Neurosurg Focus. 2006;21(4):E10.
19. Miele VJ, Carson L, Carr A, Bailes JE. Acute on chronic subdural hematoma in a female boxer: a case report. Med Sci Sports Exerc. 2004;36(11):1852-5.

20. Noble C. Hand injuries in boxing. Am J Sports Med. 1987;15(4):342-6.
21. Jordan BD, Campbell EA. Acute Injuries Among Professional Boxers in New York State: A Two-Year Survey. Phys Sportsmed. 1988;16(1):87-91.
22. Diesselhorst MM, Rayan GM, Pasque CB, Peyton Holder R. Survey of upper extremity injuries among martial arts participants. Hand Surg. 2013;18(2):151-7.
23. Doyscher R, Kraus K, Finke B, Scheibel M. [Acute and overuse injuries of the shoulder in sports]. Orthopade. 2014;43(3):202-8.
24. Wyrsch RB, Spindler KP, Stricker PR. Scapular fracture in a professional boxer. J Shoulder Elbow Surg. 1995;4(5):395-8.
25. Martin E, Lotito G, Le Corroler T, Coudreuse JM, Bensoussan L, Delarque A, et al. Teres major tendon tears in a professional boxer. Ann Phys Rehabil Med. 2014;57(9-10):727-33.
26. Enger M, Skjaker SA, Nordsletten L, Pripp AH, Melhuus K, Moosmayer S, et al. Sports-related acute shoulder injuries in an urban population. BMJ Open Sport Exerc Med. 2019;5(1):e000551.
27. Valkering KP, van der Hoeven H, Pijnenburg BC. Posterolateral elbow impingement in professional boxers. Am J Sports Med. 2008;36(2):328-32.
28. Farkash U, Dreyfuss D, Funk S, Dreyfuss U. Prevalence and Patterns of Injury Sustained During Military Hand-to-Hand Combat Training (Krav-Maga). Mil Med. 2017;182(11):e2005-e9.
29. Noble C. Hand injuries in boxing. The American Journal of Sports Medicine. 1987;15(4):342-6.
30. Davis M, Erel E, Webb J. Simultaneous bilateral third to fifth carpometacarpal joint dislocations; a boxing first? European Journal of Plastic Surgery. 2010;34(1):57-9.
31. Drury BT, Lehman TP, Rayan G. Hand and Wrist Injuries in Boxing and the Martial Arts. Hand Clin. 2017;33(1):97-106.
32. Lystad RP, Gregory K, Wilson J. The Epidemiology of Injuries in Mixed Martial Arts: A Systematic Review and Meta-analysis. Orthop J Sports Med. 2014;2(1):2325967113518492.
33. Zazryn TR, McCrory PR, Cameron PA. Injury rates and risk factors in competitive professional boxing. Clin J Sport Med. 2009;19(1):20-5.
34. Gaston RG, Loeffler BJ. Sports-specific injuries of the hand and wrist. Clin Sports Med. 2015;34(1):1-10.
35. Posner MA, Ambrose L. Boxer's knuckle--dorsal capsular rupture of the metacarpophalangeal joint of a finger. J Hand Surg Am. 1989;14(2 Pt 1):229-36.
36. Altizer L. Boxer's fracture. Orthop Nurs. 2006;25(4):271-3; quiz 4-5.
37. Cavanagh S. The true 'boxer's fracture'? Injury. 1992;23(3):204-5.
38. Iosifidis MI, Tsarouhas A, Fylaktou A. Lower limb clinical and radiographic osteoarthritis in former elite male athletes. Knee Surg Sports Traumatol Arthrosc. 2015;23(9):2528-35.
39. Crosby AC. The hands of karate experts. Clinical and radiological findings. Br J Sports Med. 1985;19(1):41-2.
40. Witkowski K, Maśliński J, Remiarz A. Static and dynamic balance in 14-15 year old boys training judo and in their non-active peers. Archives of Budo. 2014;10:323-31.
41. Koshida S, Ishii T, Matsuda T, Hashimoto T. Biomechanics of the judo backward breakfall: comparison between experienced and novice judokas. Archives of Budo. 2014;10:187-94.
42. Romaine LJ, Davis SE, Casebolt K, Harrison KA. Incidence of Injury in Kickboxing Participation. The Journal of Strength and Conditioning Research. 2003;17(3).
43. Thompson JC. Netter's Concise Orthopaedic Anatomy. Second ed. Philadelphia, PA: Saunders Elsevier; 2010.
44. Braakman M. Normal radiographic angulation in the 4th and 5th metacarpal: a reference guide. 1996;22(1):38-41.
45. Adamec J, Hofer P, Pittner S, Monticelli F, Graw M, Schöpfer J. Biomechanical assessment of various punching techniques. Int J Legal Med. 2020.
46. Lenetsky S, Brughelli M, Harris NK. Shoulder function and scapular position in boxers. Phys Ther Sport. 2015;16(4):355-60.

47. Gatt I, Smith-Moore S, Steggles C, Loosemore M. The Takei Handheld Dynamometer: An Effective Clinical Outcome Measure Tool for Hand and Wrist Function in Boxing. Hand (N Y). 2018;13(3):319-24.
48. Alberta Permanent Clinical Impairment Guide. 1996.
49. XE Currency Converter: 1 EUR to CAD = 1.53827 Canadian Dollars: XE.com Inc.; 2021 [cited 2021 January 17, 2021]. Available from: https://www.xe.com/currencyconverter/convert/?Amount=1&From=EUR&To=CAD.
50. Kadlub N, Danino A, Trost O, Robe N, Malka G. [Boxer's fracture: Cost evaluation orthopaedic or surgical treatment]. Chir Main. 2006;25(3-4):152-5.
51. CUMMINS NK, SPEARS IR. The effect of mouthguard design on stresses in the tooth-bone complex. MEDICINE & SCIENCE IN SPORTS & EXERCISE. 2001:942-7.
52. Culver JE. Sports-related fractures of the hand and wrist. Clinics in Sports Medicine. 1990;9(1):85-109.
53. Barton N. Sports injuries of the hand and wrist. Br J Sports Med. 1997;31:191-6.
54. Jordan BD, Voy RO, Stone JA. Amateur boxing injuries at the US Olympic Training Center. The Physician and Sportsmedicine. 1990;18(2):80-90.
55. Loosemore M, Lightfoot J, Gatt I, Hayton M, Beardsley C. Hand and Wrist Injuries in Elite Boxing: A Longitudinal Prospective Study (2005-2012) of the Great Britain Olympic Boxing Squad. Hand (N Y). 2017;12(2):181-7.
56. Roy B, Cardou A, Plamondon A. Influence des bandages sur la force d'impact des coups de poing a la boxe. Canadian Journal of Applied Sports Sciences. 1984;9(4):181-7.
57. Roy B, Bernier-Cardou M, Cardou A, Plamondon A. [Influence of bandages on the strength of impact of punches in boxing]. Can J Appl Sport Sci. 1984;9(4):181-7.
58. Ramazanoglu N. Effectiveness of protective foot and forearm guards in Taekwondo. Archives of Budo. 2012;8:207-11.
59. Jeong HS, O'Sullivan DM, Lee SC, Lee SY. Safety Evaluation of Protective Equipment for the Forearm, Shin, Hand and Foot in Taekwondo. J Sports Sci Med. 2019;18(2):376-83.
60. Abbott CA, Chatwin KE, Foden P, Hasan AN, Sange C, Rajbhandari SM, et al. Innovative intelligent insole system reduces diabetic foot ulcer recurrence at plantar sites: a prospective, randomised, proof-of-concept study. The Lancet Digital Health. 2019;1(6):e308-e18.
61. Beranek V, Stastny P, Novacek V, Votapek P, Formanek J. Upper Limb Strikes Reactive Forces in Mix Martial Art Athletes during Ground and Pound Tactics. Int J Environ Res Public Health. 2020;17(21).
62. Kimm D, Thiel DV. Hand Speed Measurements in Boxing. Procedia Engineering. 2015;112:502-6.
63. Worsey MT, Espinosa HG, Shepherd JB, Thiel DV. Inertial Sensors for Performance Analysis in Combat Sports: A Systematic Review. Sports (Basel). 2019;7(1).
64. Ugbolue UC, Nicol AC, Maclean J. Development and validation of an electrogoniometric wrist alignment device. Proc Inst Mech Eng H. 2008;222(5):637-46.
65. Lambert C, Beck BR, Weeks BK. Concurrent Validity and Reliability of a Linear Positional Transducer and an Accelerometer to Measure Punch Characteristics. J Strength Cond Res. 2018;32(3):675-80.
66. Svoboda M, Soukup J, Jelen K, Kubový P. Measurement of Force Impact Taekwondo Athletes, Assessing the Possibility of Injury of Human Head. Procedia Engineering. 2016;136:211-5.
67. Pierce JD, Reinbold KA, Lyngard BC, Goldman RJ, Pastore CM. Direct Measurement of Punch Force During Six Professional Boxing Matches. Journal of Quantitative Analysis in Sports. 2006;2(2).
68. Chadli S, Ababou N, Ababou A, editors. A New Instrument for Punch Analysis in Boxing. Procedia Engineering; 2014.
69. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Medicine. 2009;6(7):e1000097.

70. Gardner RC. Hypertrophic Infiltrative Tendinitis (HIT Syndrome) of the Long Extensor: The Abused Karate Hand. The Journal of the American Medical Association. 1970;211(6):1009-10.
71. McCown IA. Boxing Safety and Injuries. The Physician and Sportsmedicine. 1979;7(3):75-82.
72. Kelly DW, Pitt MJ, Mayer DM. Index Metacarpal Fractures in Karate. Phys Sportsmed. 1980;8(3):103-6.
73. Shively RA, Sundaram M. Ununited fractures of the scaphoid in boxers: A therapeutic dilemma. The American Journal of Sports Medicine. 1980;8(6):440-1.
74. VAYSSAIRAT M, PRIOLLET P, CAPRON L, HAGEGE A, HOUSSET E. Does karate injure blood vessels of the hand? The Lancet. 1984;2(8401):529.
75. Posner MA, Ambrose L. Boxer's knuckle--dorsal capsular rupture of the metacarpophalangeal joint of a finger. Journal of Hand Surgery (American). 1989;14(1):229-36.
76. Russo MT, Maffulli N. Dorsal dislocation of the distal end of the ulna in a judo player. Acta Orthopaedica Belgica. 1991;57(4):442-6.
77. Cavanagh S. The true 'boxer's fracture? Injury. 1992;23(3):204-5.
78. Chiu DTW. “Karate Kid” Finger. Plastic and Reconstructive Surgery. 1993;91(2):362-4.
79. Miller LP, Rudig L, Kreitner K-F, Degreif J. Hypothenar hammer syndrome in sports. Knee Surg, Sports Traumatol, Arthroscopy. 1996;4:167-70.
80. Porter M, O'Brien M. Incidence and Severity of Injuries Resulting From Amateur Boxing in Ireland. Clinical Journal of Sport Medicine. 1996;6:97-101.
81. Lloyd TW, Tyler MPH, Roberts AHN. Spontaneous rupture of extensor pollicis longus tendon in a kick boxer. Br J Sports Med. 1998;32:178-9.
82. Kanerva L. Knuckle pads from boxing. European Journal of Dermatology. 1998;8:359-61.
83. Hame SL, Melone CP, Jr. Boxer's knuckle in the professional athlete. The American Journal of Sports Medicine. 2000;28(6):879-82.
84. Gartland S, Malik MHA, Lovell ME. Injury and injury rates in Muay Thai kick boxing. Br J Sports Med. 2001;35:308-13.
85. Adams BB, Mutasim DF. Karate Cicatrices. Cutis. 2001;67:499-500.
86. Arai K, Nakahara K, Nishikawa S, Harata S. Treatment of soft tissue injuries to the dorsum of the metacarpophalangeal joint (Boxer's knuckle). Journal of Hand Surgery (British and European Volume). 2002;27(1):90-5.
87. Bents RT, Metz JP, Topper SM. Traumatic extensor tendon dislocation in a boxer: a case study. Med Sci Sports Exerc. 2003;35(10):1645-7.
88. Nagaoka M, Satoh T, Nagao S, Matsuzaki H. Extensor retinaculum graft for chronic boxer's knuckle. J Hand Surg Am. 2006;31(6):947-51.
89. Marie I, Herve F, Primard E, Cailleux N, Levesque H. Long-term follow-up of hypothenar hammer syndrome: a series of 47 patients. Medicine (Baltimore). 2007;86(6):334-43.
90. Melone CP, Jr., Polatsch DB, Beldner S. Disabling hand injuries in boxing: boxer's knuckle and traumatic carpal boss. Clin Sports Med. 2009;28(4):609-21,vii.
91. Durrant CA, Bantick G. Small flake, big problem: an unreported cause of extensor pollicis longus tendon rupture. Ann R Coll Surg Engl. 2010;92(1):W24-6.
92. Rizis D, Mahoney J. A Rare Presentation of Flexor Digitorum Profundus Type V Avulsion Injury with Associated Intra-Articular Fracture: A Case Report. Canadian Journal of Plastic Surgery. 2011;19(2):62-3.
93. Vidal N, Barrera-Ochoa S, Lluch A, Mir X. Simultaneous triple dislocation of the small finger. J Hand Surg Am. 2013;38(1):206.
94. Werthel JD, Masmejean E, Silvera J, Boyer P, Schlur C. Acute isolated volar dislocation of the distal radio-ulnar joint: case report and literature review. Chir Main. 2014;33(5):364-9.
95. Scoggin JF, 3rd, Brusovanik G, Izuka BH, Zandee van Rilland E, Geling O, Tokumura S. Assessment of Injuries During Brazilian Jiu-Jitsu Competition. Orthop J Sports Med. 2014;2(2):2325967114522184.

96. Nazarian N, Page RS, Hoy GA, Hayton MJ, Loosemore M. Combined joint fusion for index and middle carpometacarpal instability in elite boxers. J Hand Surg Eur Vol. 2014;39(3):242-8.
97. Siewe J, Rudat J, Zarghooni K, Sobottke R, Eysel P, Herren C, et al. Injuries in competitive boxing. A prospective study. Int J Sports Med. 2015;36(3):249-53.
98. Hashiguchi H, Iwashita S, Sawaizumi T, Ohkubo A, Takai S. Stress Fracture of the Radial Styloid Process in a Judo Player: A Case Report. J Nippon Med Sch. 2015;82(2):109-12.
99. Chang KV, Hung CY, Ozcakar L. Ultrasound imaging for the extensor pollicis brevis tendon: when martial arts caused partial rupture. Am J Phys Med Rehabil. 2015;94(2):e22.
100. Tomori Y, Ohashi R, Naito Z, Nanno M, Takai S. Florid reactive periostitis in the fifth phalange of a professional boxer: A case report. Medicine (Baltimore). 2016;95(51):e5697.
101. Koc BB, Schotanus M, Jong B, Tilman P. The Role of Dynamic Contrast-Enhanced MRI in a Child with Sport-Induced Avascular Necrosis of the Scaphoid: A Case Report and Literature Review. Case Rep Orthop. 2016;2016:7898090.
102. Kochevar A, Rayan G. Extensor Tendon Instability Due to Sagittal Band Injury in a Martial Arts Athlete: A Case Report. J Hand Surg Asian Pac Vol. 2017;22(1):93-6.
103. Tabrizi A, Afshar A. Hook Plate Fixation for the Thumb Ulnar Collateral Ligament Fracture-Avulsion. J Hand Microsurg. 2017;9(2):95-7.
104. Schweizer A, Bayer T. Closed disruption of a single flexor digitorum superficialis tendon slip: 3 cases. Hand Surg Rehabil. 2019;38(2):121-4.
105. Furuya H, Naito K, Sugiyama Y, Goto K, Nagura N, Shimamura Y, et al. Index extensor digitorum communis tendon entrapment in a growth plate injury of distal radius. Trauma Case Rep. 2019;22:100209.
106. Ribeiro LM, Botton MA. Isolated Trapezoid Fracture in a Boxer. Am J Case Rep. 2019;20:790-3.
107. Berthiaume EA, Hagopian TM, Cohen MJ, Millstein ES, Kulber DA. Surgical Repair of an Avulsed Distal Flexor Carpi Radialis Tendon in a Boxer: A Case Report. JBJS Case Connect. 2019;9(3):e0211.
108. Feder OI, Letzelter JP, Hacquebord JH. Dorsal Dislocation of the Trapezoid with Metacarpal Instability: A Boxing Injury. Journal of Wrist Surgery. 2020:1-4.
109. Noble C. Hand injuries in boxing. Am J Sports Med. 1987;15(4):342-6.
110. Diesselhorst MM, Rayan GM, Pasque CB, Peyton Holder R. Survey of upper extremity injuries among martial arts participants. Hand Surg. 2013;18(2):151-7.
111. GmbH n. Loadsol manual. Munich, Germany: novel Gmbh; 2019. p. 1-94.
112. Jones E, Peterson P, Oliphant T. Scipy 2022 [Available from: https://scipy.org/.
113. GmbH n. Novel Publications: Art in Science [updated 2022. Available from: https://www.novel.de/artinscience/.
114. Xiao Y, Yin J, Zhang X, An X, Xiong Y, Sun Y. Mechanical performance and cushioning energy absorption characteristics of rigid polyurethane foam at low and high strain rates. Polymer Testing. 2022;109.
115. Lee B, McGill S. Striking dynamics and kinetic properties of boxing and MMA gloves. Revista de Artes Marciales Asiáticas. 2014;9(2):106-15.
116. Girodet P, Durand F, Vaslin P, Lacouture P. Damping characteristics of nine samples of French boxing gloves. Computer Methods in Biomechanics and Biomedical Engineering. 2009;12(sup1):127-8.
117. Haahr M. Random.org Ireland: RANDOM.ORG; 1998-2022 [updated 2022. Available from: https://www.random.org/.
118. Canada B. Boxing Canada Articles and Rules 2017 [updated October 2017. Available from: https://boxingcanada.org/wp-content/uploads/2017/10/Rules-and-Articles-October-2017.pdf.
119. Smith PK, Hamill J. Karate and boxing glove impact. In: Terauds JaB, J.N., editor. Biomechanics in Sports II. Del Mar, CA: Academic Publishers; 1985. p. 123-33.

120. Smith PK. Transmission of force through the karate, boxing, and thumbless boxing glove as a function of velocity. . In: Terauds J, Gowitzke, B.E., & Holt, L.E., editor. Biomechanics in Sports III and IV. Del Mar, CA: Academic Publishers; 1987. p. 49-55.
121. Tjonndal A, Wagan FA. Athletes' and Coaches' Attitudes Toward Protective Headgear as Concussion and Head Injury Prevention: A Scoping Review. Frontiers in Sports and Active Living. 2021;3:13.

Appendix A – Detailed injury breakdown from systematic review (Chapter 2)

	SPORT								
FRACTURE	**Boxing**	**Karate**	**Judo**	**Kickboxing**	**Muay Thai**	**Jiu jitsu**	**Krav maga**	**Mixed Martial Arts**	**Taekwondo**
Finger phalanx	8	0	0	0	9	0	10	0	0
Finger metacarpal	19	8	0	0	10	0	7	0	0
Thumb phalanx	0	0	0	0	0	0	7	0	0
Thumb metacarpal	0	3	0	0	0	1	2	0	0
Scaphoid	0	0	0	0	0	0	12	0	0
Carpal bone (other than scaphoid)	3	0	0	0	9	0	3	0	0
Distal radius	0	0	0	0	0	0	1	0	0
Ulnar styloid	0	0	0	0	0	0	2	0	0
Complex Salter Harris 2 phalanx fracture with extensor tendon entrapment	0	0	1	0	0	0	0	0	0
TOTAL	**30**	**11**	**1**	**0**	**28**	**1**	**44**	**0**	**0**

Table A2.1 Detailed fracture breakdown based on sport subtype.

	SPORT								
JOINT INJURY	**Boxing**	**Karate**	**Judo**	**Kickboxing**	**Muay Thai**	**Jiu jitsu**	**Krav maga**	**Mixed Martial Arts**	**Taekwondo**
Finger DIP or PIP dislocation	0	0	0	0	0	1	1	0	0
Thumb CMC ligament injury	2	0	0	0	0	0	0	0	1
DRUJ injury	0	0	1	0	0	0	0	1	0
Finger CMC instability	13	0	0	0	0	0	0	0	0
Finger CMC dislocation	2	0	0	0	0	0	0	0	0
STT dislocation	1	0	0	0	0	0	0	0	0
Thumb collateral ligament injury	0	0	0	0	0	0	4	0	0
Complex multijoint dislocation (PIP/DIP/CMC of one finger)	0	1	0	0	0	0	0	0	0
TOTAL	**18**	**1**	**1**	**0**	**0**	**1**	**5**	**1**	**1**

Table A2.2. Detailed joint injury breakdown based on sport subtype.

CONTUSION/ SPRAIN	SPORT								
	Boxing	Karate	Judo	Kickboxing	Muay Thai	Jiu jitsu	Krav maga	Mixed Martial Arts	Taekwondo
Finger DIP, PIP, CMC or phalanx contusion/sprain/ abrasion	4	0	0	0	0	1	35	0	0
Thumb IP or phalanx contusion/sprain/ abrasion	0	0	0	0	6	1	83	0	0
Hand/wrist contusion/sprain/ abrasion	24	0	0	0	10	0	107	0	0
TOTAL	**28**	**0**	**0**	**0**	**16**	**2**	**225**	**0**	**0**

Table A2.3. Detailed contusion/sprain injury breakdown based on sport subtype.

SOFT TISSUE	SPORT								
	Boxing	Karate	Judo	Kickboxing	Muay Thai	Jiu jitsu	Krav maga	Mixed Martial Arts	Taekwondo
Extensor Hood rupture	86	2	0	0	0	0	0	0	1
Finger flexor tendon avulsion/tear/ intrasubstance injury	0	2	0	0	0	0	0	0	1
Finger extensor tendon avulsion/tear/ intrasubstance injury	3	1	0	0	0	0	0	0	0
Wrist flexor tendon avulsion	1	0	0	0	0	0	0	0	0
Wrist extensor tendon avulsion/tear/ intrasubstance injury	1	0	0	0	0	0	0	1	0
EPL rupture	0	0	0	1	0	0	0	1	0
EPB rupture (partial)	0	0	0	0	0	0	0	1	0
Ulnar wrist capsule rupture	1	0	0	0	0	0	0	0	0
Laceration	1	0	0	0	0	0	3	0	0
TOTAL	**93**	**5**	**0**	**1**	**0**	**0**	**3**	**3**	**2**

Table A2.4. Detailed soft tissue injury breakdown based on sport subtype.

NEUROVASCULAR	SPORT								
	Boxing	Karate	Judo	Kickboxing	Muay Thai	Jiu jitsu	Krav maga	Mixed Martial Arts	Taekwondo
FINGER									
Nerve	0	0	0	0	0	0	0	0	0
Vascular	0	1	0	0	0	0	0	0	0
HAND									
Nerve	0	0	0	0	0	0	0	0	0
Vascular	0	2	0	0	0	0	0	0	0
TOTAL	**0**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table A2.5. Detailed neurovascular injury breakdown based on sport subtype.

CHRONIC	SPORT								
	Boxing	Karate	Judo	Kickboxing	Muay Thai	Jiu jitsu	Krav maga	Mixed Martial Arts	Taekwondo
Scaphoid non-union	3	0	0	0	0	0	0	0	0
Scaphoid AVN	0	1	0	0	0	0	0	0	0
Carpal boss	11	0	0	0	0	0	0	0	0
Reactive periostitis finger/MC	1	0	0	0	0	0	0	0	0
Knuckle pads	1	0	0	0	0	0	0	0	0
Scars to back of hand	0	1	0	0	0	0	0	0	0
Radial styloid stress fracture	0	0	1	0	0	0	0	0	0
Ulnar digital nerve fibrosis	0	1	0	0	0	0	0	0	0
Chronic pain/swelling to index finger MCP	1	0	0	0	0	0	0	0	0
TOTAL	**17**	**3**	**1**	**0**	**0**	**0**	**0**	**0**	**0**

Table A2.6. Detailed chronic repetitive impact injury breakdown based on sport subtype.

FRACTURE	EXPERIENCE				
	Elite or Professional	Amateur or Recreational	Military or Police	Pediatric (<18 years of age)	Unknown
Finger phalanx	8	0	10	0	9
Finger metacarpal	17	10	7	0	10
Thumb phalanx	0	0	7	0	0
Thumb metacarpal	0	4	2	0	0
Scaphoid	0	0	12	0	0
Carpal bone (other than scaphoid)	1	2	3	0	9
Distal radius	0	0	1	0	0
Ulnar styloid	0	0	2	0	0
Complex Salter Harris 2 phalanx fracture with extensor tendon entrapment	0	0	0	1	0
TOTAL	**26**	**16**	**44**	**1**	**28**

Table A2.7. Detailed fracture breakdown based on experience level.

JOINT	EXPERIENCE				
	Elite or Professional	Amateur or Recreational	Military or Police	Pediatric (<18 years of age)	Unknown
Finger DIP or PIP dislocation	0	1	1	0	0
Thumb CMC ligament injury	0	3	0	0	0
DRUJ injury	0	0	1	0	1
Finger CMC instability	13	0	0	0	0
Finger CMC dislocation	2	0	0	0	0
STT dislocation	1	0	0	0	0
Thumb collateral ligament injury	0	0	4	0	0
Complex multijoint dislocation (PIP/DIP/CMC of one finger)	0	0	0	0	1
TOTAL	**16**	**4**	**6**	**0**	**2**

Table A2.8. Detailed joint injury breakdown based on experience level.

CONTUSION/ SPRAIN	EXPERIENCE				
	Elite or Professional	Amateur or Recreational	Military or Police	Pediatric (<18 years of age)	Unknown
Finger DIP, PIP, CMC or phalanx contusion/sprain/ abrasion	4	1	35	0	0
Thumb IP or phalanx contusion/sprain/ abrasion	0	1	83	0	6
Hand/wrist contusion/sprain/ abrasion	23	1	107	0	10
TOTAL	**27**	**3**	**225**	**0**	**16**

Table A2.9. Detailed contusion/sprain injury breakdown based on experience level.

SOFT TISSUE	EXPERIENCE				
	Elite or Professional	Amateur or Recreational	Military or Police	Pediatric (<18 years of age)	Unknown
Extensor hood rupture	81	7	0	1	0
Finger flexor tendon avulsion/tear/ intrasubstance injury	0	0	1	0	2
Finger extensor tendon avulsion/tear/ intrasubstance injury	2	1	1	0	0
Wrist flexor tendon avulsion	1	0	0	0	0
Wrist extensor tendon avulsion/tear/ intrasubstance injury	0	1	0	0	1
EPL rupture	1	0	0	0	1
EPB partial rupture	0	0	0	0	1
Ulnar wrist capsule rupture	1	0	0	0	0
Laceration	1	0	3	0	0
TOTAL	**87**	**9**	**5**	**1**	**5**

Table A2.10. Soft tissue injury breakdown based on experience level.

NEUROVASCULAR	EXPERIENCE				
	Elite or Professional	Amateur or Recreational	Military or Police	Pediatric (<18 years of age)	Unknown
FINGER					
Nerve	0	0	0	0	0
Vascular	1	0	0	0	0
HAND					
Nerve	0	0	0	0	0
Vascular	1	0	0	0	1
TOTAL	**2**	**0**	**0**	**0**	**1**

Table A2.11. Detailed neurovascular injury breakdown based on experience level.

CHRONIC	EXPERIENCE				
	Elite or Professional	Amateur or Recreational	Military or Police	Pediatric (<18 years of age)	Unknown
Scaphoid non-union	3	0	0	0	0
Scaphoid AVN	0	0	0	1	0
Carpal boss	11	0	0	0	0
Reactive periostitis finger/MC	1	0	0	0	0
Knuckle pads	0	1	0	0	0
Scars to back of hand	0	0	0	0	1
Radial styloid stress fracture	0	0	0	1	0
Ulnar digital nerve fibrosis	0	0	0	1	0
Chronic pain/swelling index MCP	1	0	0	0	0
TOTAL	**16**	**1**	**0**	**3**	**1**

Table A2.12. Detailed chronic injury breakdown based on experience level.

FRACTURE	SPORT TYPE		
	Striking only	Throws only	Striking and throws
Finger phalanx	8	0	19
Finger metacarpal	19	0	25
Thumb phalanx	0	0	7
Thumb metacarpal	0	1	5
Scaphoid	0	0	12
Carpal bone (other than scaphoid)	3	0	12
Distal radius	0	0	1
Ulnar styloid	0	0	2
Complex Salter Harris 2 phalanx fracture with extensor tendon entrapment	0	1	0
TOTAL	**30**	**2**	**83**

Table A2.13. Detailed fracture breakdown based on mechanism of combat.

JOINT	SPORT TYPE		
	Striking only	Throws only	Striking and throws
Finger DIP or PIP dislocation	0	1	1
Thumb CMC ligament injury	2	0	1
DRUJ injury	0	1	1
Finger CMC instability	13	0	0
Finger CMC dislocation	2	0	0
STT dislocation	1	0	0
Thumb collateral ligament injury	0	0	4
Complex multijoint dislocation (PIP/DIP/CMC of one finger)	0	0	1
TOTAL	**18**	**2**	**8**

Table A2.14. Detailed joint injury breakdown based on mechanism of combat.

CONTUSION/ SPRAIN	SPORT TYPE		
	Striking only	Throws only	Striking and throws
Finger DIP, PIP or phalanx contusion/sprain/ abrasion	4	1	35
Thumb IP or phalanx contusion/sprain/ abrasion	0	1	89
Hand/wrist contusion/sprain/ abrasion	24	0	117
TOTAL	28	2	241

Table A2.15. Detailed contusion/sprain injury breakdown based on mechanism of combat.

SOFT TISSUE	SPORT TYPE		
	Striking only	Throws only	Striking and throws
Extensor hood rupture	86	0	3
Finger flexor tendon avulsion/tear/ intrasubstance injury	0	2	1
Finger extensor tendon avulsion/tear/ intrasubstance injury	3	0	1
Wrist flexor tendon avulsion	1	0	0
Wrist extensor tendon avulsion/tear/ intrasubstance injury	1	0	1
EPL rupture	1	0	1
EPB partial rupture	0	0	1
Ulnar wrist capsule rupture	1	0	0
Laceration	1	0	3
TOTAL	94	2	11

Table A2.16. Detailed soft tissue injury breakdown based on mechanism of combat.

NEUROVASCULAR	SPORT TYPE		
	Striking only	Throws only	Striking and throws
FINGER			
Nerve	0	0	0
Vascular	0	0	1
HAND			
Nerve	0	0	0
Vascular	0	0	2
TOTAL	**0**	**0**	**3**

Table A2.17. Detailed neurovascular injury breakdown based on mechanism of combat.

CHRONIC	SPORT TYPE		
	Striking only	Throws only	Striking and throws
Scaphoid non-union	3	0	0
Scaphoid AVN	0	0	1
Carpal boss	11	0	0
Reactive periostitis finger/MC	1	0	0
Knuckle pads	1	0	0
Scars to back of hand	0	0	1
Radial styloid stress fracture	0	1	0
Ulnar digital nerve fibrosis	0	0	1
Chronic pain/swelling index MCP	1	0	0
TOTAL	**17**	**1**	**3**

Table A2.18. Detailed chronic injury breakdown based on mechanism of combat.

	INJURY ACUITY			
FRACTURE	Acute	Chronic	Acute on chronic	Unknown
Finger phalanx	19	0	0	8
Finger metacarpal	29	0	0	15
Thumb phalanx	7	0	0	0
Thumb metacarpal	6	0	0	0
Scaphoid	12	0	0	0
Carpal bone (other than scaphoid)	15	0	0	0
Distal radius	1	0	0	0
Ulnar styloid	2	0	0	0
Complex Salter Harris 2 phalanx fracture with extensor tendon entrapment	1	0	0	0
TOTAL	**92**	**0**	**0**	**23**

Table A2.19. Detailed fracture breakdown based on injury acuity.

	INJURY ACUITY			
JOINT	Acute	Chronic	Acute on chronic	Unknown
Finger DIP or PIP dislocation	2	0	0	0
Thumb CMC ligament injury	3	0	0	0
DRUJ injury	2	0	0	0
Finger CMC instability	0	13	0	0
Finger CMC dislocation	2	0	0	0
STT dislocation	1	0	0	0
Thumb collateral ligament injury	4	0	0	0
Complex multijoint dislocation (PIP/DIP/CMC of one finger)	1	0	0	0
TOTAL	**15**	**13**	**0**	**0**

Table A2.20. Detailed joint injury breakdown based on injury acuity.

CONTUSION/ SPRAIN	INJURY ACUITY			
	Acute	Chronic	Acute on chronic	Unknown
Finger DIP, PIP or phalanx contusion/sprain/ abrasion	40	0	0	0
Thumb IP or phalanx contusion/sprain/ abrasion	90	0	0	0
Hand/wrist contusion/sprain/ abrasion	141	0	0	0
TOTAL	**271**	**0**	**0**	**0**

Table A2.21. Detailed contusion/sprain injury breakdown based on injury acuity.

SOFT TISSUE	INJURY ACUITY			
	Acute	Chronic	Acute on chronic	Unknown
Extensor hood rupture	4	58	0	27
Finger flexor tendon avulsion/tear/ intrasubstance injury	3	0	0	0
Finger extensor tendon avulsion/tear/ intrasubstance injury	1	3	0	0
Wrist flexor tendon avulsion	1	0	0	0
Wrist extensor tendon avulsion/tear/ intrasubstance injury	2	0	0	0
EPL rupture	2	0	0	0
EPB partial rupture	1	0	0	0
Ulnar wrist capsule rupture	0	1	0	0
Laceration	4	0	0	0
TOTAL	**18**	**62**	**0**	**27**

Table A2.22. Detailed soft tissue injury breakdown based on injury acuity.

NEUROVASCULAR	INJURY ACUITY			
	Acute	Chronic	Acute on chronic	Unknown
FINGER				
Nerve	0	0	0	0
Vascular	0	1	0	0
HAND				
Nerve	0	0	0	0
Vascular	0	1	0	1
TOTAL	**0**	**2**	**0**	**1**

Table A2.23. Detailed neurovascular injury breakdown based on injury acuity.

CHRONIC	INJURY ACUITY			
	Acute	Chronic	Acute on chronic	Unknown
Scaphoid non-union	0	2	1	0
Scaphoid AVN	0	1	0	0
Carpal boss	0	11	0	0
Reactive periostitis finger/MC	0	1	0	0
Knuckle pads	0	1	0	0
Scars to back of hand	0	1	0	0
Radial styloid stress fracture	0	0	1	0
Ulnar digital nerve fibrosis	0	1	0	0
Chronic pain/swelling index MCP	0	1	0	0
TOTAL	**0**	**19**	**2**	**0**

Table A2.24. Detailed chronic injury breakdown based on injury acuity.

	TRAINING		
FRACTURE	Match or competition	Training	Unknown
Finger phalanx	0	10	17
Finger metacarpal	2	7	35
Thumb phalanx	0	7	0
Thumb metacarpal	1	2	3
Scaphoid	0	12	0
Carpal bone (other than scaphoid)	2	4	9
Distal radius	0	1	0
Ulnar styloid	0	2	0
Complex Salter Harris 2 phalanx fracture with extensor tendon entrapment	0	0	1
TOTAL	**5**	**45**	**65**

Table A2.25. Detailed fracture breakdown based on timing of injury during competition or training.

	TRAINING		
JOINT	Match or competition	Training	Unknown
Finger DIP or PIP dislocation	1	1	0
Thumb CMC ligament injury	3	0	0
DRUJ injury	0	1	1
Finger CMC instability	0	0	13
Finger CMC dislocation	2	0	0
STT dislocation	1	0	0
Thumb collateral ligament injury	0	4	0
Complex multijoint dislocation (PIP/DIP/CMC of one finger)	0	0	1
TOTAL	**7**	**6**	**15**

Table A2.26. Detailed joint injury breakdown based on timing of injury during competition or training.

CONTUSION/ SPRAIN	TRAINING		
	Match or competition	Training	Unknown
Finger DIP, PIP or phalanx contusion/sprain/ abrasion	1	35	4
Thumb IP or phalanx contusion/sprain/ abrasion	1	83	6
Hand/wrist contusion/sprain/ abrasion	1	107	33
TOTAL	**3**	**225**	**43**

Table A2.27. Detailed contusion/sprain injury breakdown based on timing of injury during competition or training.

SOFT TISSUE	TRAINING		
	Match or competition	Training	Unknown
Extensor hood rupture	1	0	88
Finger flexor tendon avulsion/tear/ intrasubstance injury	0	2	1
Finger extensor tendon avulsion/tear/ intrasubstance injury	1	1	2
Wrist flexor tendon avulsion	0	0	1
Wrist extensor tendon avulsion/tear/ intrasubstance injury	1	0	1
EPL rupture	0	1	1
EPB partial rupture	0	0	1
Ulnar wrist capsule rupture	0	0	1
Laceration	0	3	1
TOTAL	**3**	**7**	**97**

Table A2.28. Detailed soft tissue injury breakdown based on timing of injury during competition or training.

NEUROVASCULAR	TRAINING		
	Match or competition	Training	Unknown
FINGER			
Nerve	0	0	0
Vascular	0	0	1
HAND			
Nerve	0	0	0
Vascular	0	0	2
TOTAL	**0**	**0**	**3**

Table A2.29. Detailed neurovascular injury breakdown based on timing of injury during competition or training.

CHRONIC	TRAINING		
	Match or competition	Training	Unknown
Scaphoid non-union	0	0	3
Scaphoid AVN	0	0	1
Carpal boss	0	0	11
Reactive periostitis finger/MC	0	0	1
Knuckle pads	0	0	1
Scars to back of hand	0	0	1
Radial styloid stress fracture	0	1	0
Ulnar digital nerve fibrosis	0	1	0
Chronic pain/swelling index MCP	0	0	1
TOTAL	**0**	**2**	**19**

Table A2.30. Detailed chronic injury breakdown based on timing of injury during competition or training.

Appendix B – Recruitment Poster

ROTH | McFARLANE HAND & UPPER LIMB CENTRE ST. JOSEPH'S HEALTH CARE LONDON

Western UNIVERSITY · CANADA

ST JOSEPH's HEALTH CARE LONDON

Help us learn about how different types of hand wraps protect your hands while boxing

Study participation involves:

- Coming to the gym for 2 days (for about one hour each day)
- Wearing hand/wrist sensors while throwing punches on the aqua bag using hand wraps one day and gel wraps the other day
- Filling out a short paper survey

Version date: 2021/03/12

Appendix C – Paper Survey

Force analysis of protective hand wraps in combat athletes

Participant Number: _________

Age: ______________years

Gender: ☐ Male ☐ Female ☐ Prefer not to answer

Height: _________feet ____________inches

Weight: _____________pounds

Preferred stance/handedness: ☐ Orthodox ☐ Southpaw AND ☐ Right ☐ Left

Experience: _______years ________months

Level of practice: ☐ Professional ☐ Amateur ☐ Recreational

Field of practice: ☐ Boxing ☐ Muay Thai ☐ Mixed Martial Arts (MMA)
(check all that apply) ☐ Other ______________________

Previous upper extremity injury:
____
____
____

Type of hand wrap preferred:

A. Pre-study: ☐ Linear wraps ☐ Gel reinforced wraps ☐ Other _______________
B. Post study: ☐ Linear wraps ☐ Gel reinforced wraps ☐ Other _______________

Better performance during the study protocol: ☐ Linear wraps ☐ Gel reinforced wraps

Curriculum Vitae

Eva Marie Gusnowski

Post Graduate Education

2021-2022	*University of Manitoba* – Clinical Fellow, Sports and Upper Extremity Reconstruction
2020-2021	*University of Western Ontario* – Clinical Fellow, Shoulder Surgery Fellowship Program
2015-2020	*University of Calgary* – PGME Orthopaedic Surgery Residency Program
2011-2015	*University of British Columbia* – M.D. Undergraduate Program
2008-2010	*University of Alberta* – M.Sc. Molecular Biology and Genetics
2003-2008	*University of Alberta* – B.Sc. Honors Molecular Genetics, First Class Honors

Research Experience

2020-Present	*M.Sc. Surgery Graduate Student, University of Western Ontario*
2015-2020	*Resident Researcher, University of Calgary*
2012, 2013	*Summer Research Assistant, Fraser Valley Cancer Center*
2008-2011	*M.Sc. Graduate Student, University of Alberta*
2008	*Summer Research Assistant, University of Alberta*
2007-2008	*Honors Thesis Project, University of Alberta*
2007	*Summer Research Assistant, University of Alberta*

Conference Activities

- Gusnowski, Eva M., Serene W. Wohlgemuth, and Dave B. Pilgrim. 2008. Myosin chaperones in zebrafish development. CDBC. February 28-March 1, 2008. Banff, Alberta, Canada. (Poster presentation)
- Gusnowski, Eva M. and Martin A. Srayko. 2010. CDBC. Dynein contributes to lateral microtubule velocity at the inner cortex of the one-cell *C.elegans* embryo. April 9-11, 2010. Mont Tremblant, Quebec, Canada. (Poster presentation)
- Gusnowski, Eva M. and Paris-Ann Ingledew. 2012. Getting to the bottom of things: Quality of online resources for colorectal cancer patients. November 29-December 1, 2012. Vancouver, British Columbia, Canada. (Poster Presentation)
- Gusnowski, Eva M. and Paris-Ann Ingledew. 2013. Quality of online resources for colorectal cancer patients. January 24-26, 2013. Carmel, California, USA. (Podium presentation)
- Gusnowski, Eva M. and Paris-Ann Ingledew. 2013. Getting to the bottom of things: Quality of online resources for colorectal cancer patients. February 18, 2013. Vancouver, British Columbia, Canada. (Poster and Podium Presentation)
- Gusnowski, Eva M. and Prism S. Schneider. 2017. Meta-analysis of complications in dorsal versus volar distal radius plating. Department of Surgery Resident Research Day. June 2017. Calgary, Alberta, Canada. (Podium Presentation).

- Gusnowski, Eva M. and Prism S. Schneider. 2018. There is no difference in tendon rupture rate between dorsal and volar plate fixation for distal radius fractures. Orthopaedic Surgery Resident Research Day. April 26, 2018. Calgary, Alberta, Canada. (Podium Presentation).
- Gusnowski, Eva M. and Prism S. Schneider. 2018. There is no difference in tendon rupture rate between dorsal and volar plate fixation for distal radius fractures. Department of Surgery Resident Research Day. June 15, 2018. Calgary, Alberta, Canada. (Poster Presentation).
- Gusnowski, Eva M. and Prism S. Schneider. 2018. There is no difference in tendon rupture rate between dorsal and volar plate fixation for distal radius fractures. CORA Annual Meeting. June 22, 2018. Calgary, Alberta, Canada. (Poster Presentation).
- Gusnowski, Eva M. and Prism S. Schneider. 2018. There is no difference in tendon rupture rate between dorsal and volar plate fixation for distal radius fractures. COA Annual meeting. June 23, 2018. Victoria, BC, Canada. (Podium Presentation).
- Gusnowski, Eva M., Cory A. Kwong, Jarret M. Woodmass, Aaron Bois, Justin LeBlanc, Marlis Sabo and Ian K.Y. Lo. The Effect of Platelet Rich Plasma on Partial Thickness Rotator Cuff Tears: A Double-Blinded Prospective Randomized Control Trial. Orthopaedic Resident Research Day, University of Calgary. April 25, 2019 (Podium Presentation)
- Gusnowski, Eva M., Cory A. Kwong, Jarret M. Woodmass, Aaron Bois, Justin LeBlanc, Marlis Sabo and Ian K.Y. Lo. The Effect of Platelet Rich Plasma on Partial Thickness Rotator Cuff Tears: A Double-Blinded Prospective Randomized Control Trial. AANA Annual Meeting. May 2-4, 2019 (Podium Presentation)
- Gusnowski, Eva M., Kate Thomas and Prism S. Schneider. Comparison of Range of Motion Between Dorsal and Volar Plate Fixation for Distal Radius Fractures. COA Annual meeting. June 19-22, 2019. Montreal, QC, Canada. (Podium Presentation)
- Gusnowski, Eva M., Kate Thomas and Prism S. Schneider. Comparison of Range of Motion Between Dorsal and Volar Plate Fixation for Distal Radius Fractures. OOA Annual meeting. November 5, 2020. London, ON, Canada. (Oral Presentation)

<u>Publications</u>

- Gusnowski, E.M. and M. Srayko. 2011. Visualization of dynein-dependent microtubule gliding at the cell cortex: implications for spindle positioning. *Journal of Cell Biology.* **194**(3):377.
- Gusnowski, E.M. and P. Ingledew. 2013. Quality of online resources for colorectal cancer patients (Abstract). Western AFMR Conference, Carmel, California.
- Tegha-Dunghu, J., E.M. Gusnowski and M. Srayko. 2014. Measuring Microtubule Growth and Gliding in Caenorhabditis elegans Embryos. *Methods in Molecular Biology*. **1136**:103-116.
- Hamilton, S.H., E. P. Scali, I. Yu, E. Gusnowski and P. Ingledew. 2014. Sifting Through It All: Characterizing Melanoma Patients' Utilization of the Internet as an Information Source (Epub). *Journal of Cancer Education*. DOI: 10.1007/s13187-014-0711-1.

- Kwong, C.A., E.M. Gusnowski, K.K.W. Tam and I.K.Y. Lo. 2017. Assessment of Bone Loss in Anterior Shoulder Instability. *Annals of Joint*. **63**(2):1-9.
- Gusnowski, E.M. and P.S. Schneider. 2018. There is No Difference in Tendon Rupture Rate Between Dorsal and Volar Plate Fixation for Distal Radius Fractures (Abstract). COA Annual Meeting, Victoria, BC.
- Gusnowski, E.M., C.A. Kwong, J.M. Woodmass, A. Bois, J. LeBlanc, M. Sabo and I.K.Y. Lo. The Effect of Platelet Rich Plasma on Partial Thickness Rotator Cuff Tears: A Double-Blinded Prospective Randomized Control Trial. AANA Annual Meeting. May 2-4, 2019 (Abstract).
- Gusnowski, E.M., K. Thomas and P.S. Schneider. Comparison of Range of Motion Between Dorsal and Volar Plate Fixation for Distal Radius Fractures. COA Annual meeting. June 19-22, 2019. Montreal, QC, Canada (Abstract).
- Wang, L., E.M. Gusnowski and P.A. Ingledew. 2020. Digesting the contents: An analysis of online colorectal cancer education websites. *Journal of Cancer Education*. https://doi.org/10.1007/s13187-020-01864-5
- Gusnowski, E.M., L.J. Morrison and A.J. Bois. 2020. Infectious Brachial Plexopathy and Septic Arthritis of the Shoulder due to Lemierre's Syndrome: A Case Report and Literature Review. *JBJS Case Connector*. **10(4):**e20.00362. doi:10.2106/JBJS.CC.20.00362
- Kwong, C.A., J.M. Woodmass, E.M. Gusnowski, A.J. Bois, J. Leblanc, K.D. More, I.K.Y. Lo. 2021. Platelet-Rich Plasma in patients with partial-thickness rotator cuff tears or tendinopathy leads to significantly improved short-term pain relief and function compared with corticosteroid injection: a double-blind randomized controlled trial. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*. **37**(2):510-517.

Awards

2020	Honorable Mention, PGME Resident Teaching Award (Calgary, AB)
2019	First place, Podium Lightning Presentation, 2019 CORA Annual Meeting (Montreal, QC)
	Stephen S. Burkhart Shoulder Innovation Research Award, 2019 AANA Annual Meeting (Orlando, FL)
	Second Place Podium Presentation, Calgary Orthopaedic Resident Research Day (Calgary, AB)
	COREF Grant for group project (Calgary, AB)
2018	COREF Grant for individual and group projects (Calgary, AB)
	Poster Presentation Award (Best Clinical Research Poster), University of Calgary Surgeon's Day (Calgary, AB)
2013	Poster Presentation (Honorable Mention) Award, Faculty of Medicine Research Forum (Vancouver, BC)
2012	Poster Presentation Award, BC Cancer Agency Conference (Vancouver, BC)
	BC Cancer Agency, Summer Studentship (Surrey, BC)
2011	Leadership Award, Campus Food Bank (Edmonton, Alberta)

2010	Poster Presentation Award, Canadian Developmental Biology Conference (Mont. Tremblant, QC)
2008	NSERC CGS-M Alexander Graham Bell Graduate Scholarship
	Alberta Ingenuity Fund Graduate Scholarship
	Walter H. Johns Graduate Fellowship
	Department of Biology Graduate Entrance Scholarship
	NSERC Summer Studentship
	Outstanding Research in Genetics Prize
	Dean's Silver Medal in Science
2007	NSERC Summer Studentship
	Alberta Heritage Foundation for Medical Research Summer Studentship