Effects of bandaging techniques and shot types on wrist motion in boxing

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Effects of Bandaging Techniques and Shot Types on Wrist Motion in Boxing

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Candidate Declaration

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2. None of the material contained in the thesis has been used in any other submission for an academic award.

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Award	PhD
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Abstract

Hand-Wrist injuries account for the highest number of injuries in Boxing. Bandaging of the hand-wrist region is a common and historic practice in this sport. However, there is no literature exploring the effect of bandaging techniques on wrist motion in boxing or other combat sports. This programme of research was aimed at improving the knowledge of wrist kinematics on impact in boxing through a rigorous scientific approach.

Three novel studies were generated and published in peer-reviewed journals The first study describes a new method for quantifying wrist motion in boxing using an electromagnetic tracking system. Surrogate testing procedure utilising a polyamide hand and forearm shape, and *in-vivo* testing procedure utilising 29 elite boxers, were used to assess the accuracy and repeatability of the system. Two-dimensional kinematic analysis was used to calculate wrist angles using photogrammetry, whilst the data from the electromagnetic tracking system was processed with Visual 3D software. The electromagnetic tracking system agreed with the video-based system in both the surrogate (<0.2°) and quasi-static testing (<6°). Both systems showed a good intraclass coefficient of reliability (ICCs >0.9). In the punch testing, the electromagnetic tracking system showed good reliability (ICCs >0.8) and substantial reliability (ICCs >0.6) for flexion-extension and radial-ulnar deviation angles respectively.

The second study quantified wrist motion during *in-vivo* impact testing procedures for two types of shots, Jab (straight arm shot) and Hook (bent arm short), with 29 elite boxers. For both shots, flexion and ulnar deviation occurred concurrent on impact, with a mean and standard deviation of 9.3±1.9° and 4.7±1.2° respectively for Jab shots, and 5.5±1.1° and 3.3±1.1° respectively for Hook shots, supporting dart throwing motion at the wrist. For both Jab & Hook, wrist motion on impact occurred within >30% and >20% respectively of total available active range of motion, with wrist angles greater in both flexion ($t=9.0$, $p<0.001$, $d=1.7$) and ulnar deviation ($t=8.4$, $p<0.001$, $d=1.6$) for Jab compared to Hook shots.

The third study investigated the effects of bandaging techniques on wrist motion on impact during two shot types, Jab (straight arm shot) and Hook (bent arm short), in 18 elite male boxers wearing either bandage only or bandage plus tape. For both motions, a significant ($p<0.001$) interaction between bandage techniques and shot types, and significant ($p<0.001$) main effects for bandaging techniques ($\eta^2=0.580\text{-}0.729$) and shot types ($\eta^2=0.165\text{-}0.280$), were observed. For straight and bent arm shots, wrist motion on impact occurred within 50% and 40% respectively of total active wrist motion for bandage only compared to within 20% and 15% for bandage plus tape. Time to peak wrist angle on impact increased significantly ($p<0.001$) by 1.2-1.4 for both shot types when adding tape to bandage.

The information from this programme of research contributes to knowledge through a better understanding of wrist kinematics on impact in boxing, useful towards both injury prevention and management strategies. Further, the methodology and knowledge discussed is applicable to wider clinical and scientific settings.

Acknowledgements

"And, when you want something, all the universe conspires in helping you to achieve it." Paulo Coelho, The Alchemist, 1988.

This programme of research was a work of passion, derived from personal interest in better understanding wrist motion on impact in boxing and the effect of bandaging techniques. It was a difficult journey that tested my resilience. To achieve the objectives set from the onset, the universe did conspire in helping me, albeit in its own satirical manner.

Boxing is considered an individual sport, however, a team effort is always required to achieve success. I therefore need to acknowledge the team that was there for me.

Firstly, a big shout out to my supervisors who showed me the ropes, Professor Jon Wheat and Dr Tom Allen. I could not have asked for a better team in my corner. Challenging and supporting throughout the whole process, allowed me to go the full distance. I would also like to extend my thanks to all the members of the Advanced Wellbeing Research Centre who assisted when needed, Simon Goodwill, Nick Hamilton, Katy J Nunn, Ben Heller, Ian Brookes, Claire Cutt, Rea Smith, and Caroline White (a former fellow PhD student at Sheffield Hallam University).

To all the staff and boxers at both Great Britain Boxing and UK Sports Institute, who helped at different times during the studies, thanks for your contribution.

To my family and partner Lyndsay, thanks for your patience and support.

Luigi, my son, you were always there along the journey.

Supporting Materials

Peer-Reviewed Publications

Gatt I, Allen, T., Wheat, J. (2023) Effects of using rigid tape with bandaging techniques on wrist joint motion during boxing shots in elite male athletes. *Physical Therapy in Sport*, 18(61), pp. 82-90.

Gatt I, Allen, T., Wheat, J. (2021) Quantifying wrist angular excursion on impact for Jab and Hook lead arm shots in boxing. *Sports Biomechanics* 6, pp. 1-13.

Gatt, I.T., Allen, T. and Wheat, J. (2020) Accuracy and repeatability of wrist joint angles in boxing using an electromagnetic tracking system. Sports Engineering 23, 2

Abstracts Submitted at Conferences (With Presentations)

Gatt, I.T. Bridging the Gap between Research and Applied Practice in Sports. Keynote Speaker. In: *World Conference on Orthopaedics, Sprots Medicine and Rehabilitation*, Barcelona May 18th, 2023.

Gatt, I.T. CMC Injuries in Boxing. In: *BOSTAA Annual National Conference,* USA. July 14th, 2021.

Gatt, I.T., Allen, T. and Wheat J. Quantifying wrist motion in boxing. In: *National Biomechanics Day*. BASES. Solent University, Southampton. April 7th, 2021.

Gatt, I.T., Allen, T. and Wheat, J. Validity and Repeatability of wrist joint angles in Boxing using the Polhemus markerless motion capture system. In: *Measuring Behaviour in Sports*. Manchester June 6-8th, 2018.

Presentations Given (Specific to this Programme of Research)

Gatt, I.T. Hand Injuries in Boxing. In: *School of Health Sciences*; University of Nottingham April 21st, 2023.

Gatt, I. Hand and Wrist Injuries in Boxing; Are They Easy to Manage In: *Belgium Hand Therapy Symposium Conference*. Belgium. Oct 22nd, 2022.

Gatt, I. UpperLimb Injuries in Combat Sports. In: *Swiss UpperLimb Symposium*, Geneve. May 12th, 2022.

Gatt, I. Hand Injuries in Boxing. In: *Boxing Science Conference*, Sheffield. May 2nd, 2022.

Gatt, I. Hand Injuries in Boxing; how research aligns with applied clinical questions. In: *Research Seminar Series*, Liverpool Hope University. Feb 16th, 2022.

Gatt, I. The Art of Boxing. In: *An Evening of Boxing*; Queen Mary University of London. April 15th, 2021.

Gatt, I. Boxing Return to Play following Hand-Wrist Injuries. In: *British Society for Surgery of the Hand*, Swansea. April 25th, 2019.

Gatt, I. Boxing Injuries. In: *Elite Sports Expo*, Birmingham. Nov 21-22nd 2018.

Gatt, I. Hand Wraps and Injury Prevention. In: *British Association of Hand Therapists; Expanding Hand Therapy Practice*. Birmingham Nov 9-10th, 2018.

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Abbreviations

3D	Three Dimensional
AROM	Available Active Range of Motion
BC	Before Christ
CMC	Carpometacarpal
CSM	Consecutive sequence of motion
ECRB	Extensor Carpi Radialis Brevis
ECRL	Extensor Carpi Radialis Longus
EXT	Extension
FCU	Flexor Carpi Ulnaris
FLEX	Flexion
GB	Great Britain
hr	hour
JPS	Joint position sense
OG	Olympic Games
oz	Ounce
m	Metre
m/s	Metres per Second
MC	Metacarpal
MCP	Metacarpophalangeal
MiC	Midcarpal
MRI	Magnetic Resonance Imaging
MVC	Maximum Voluntary Contraction
Ns/Kg	Newton Second Per Kilogram
RC	Radio-Carpal
RD	Radial Deviation
ROM	Range of Motion
SLT-CH	Scapholunotriquetrum-capitate-hamate
SSM	Sequential sequence of motion
STT	Scaphotrapeziotrapezoid
TROM	Total Active Range of Motion
UD	Ulnar Deviation

1.0 Introduction

This programme of research investigates differences between bandaging techniques, and shot types, on wrist motion on impact in boxing. Impact was defined as the contact of the boxer's glove with a boxing bag. A novel method was developed to quantify wrist motion on impact in boxing. This initial chapter explains the rationale for conducting the research, outlining the aims it was set out to achieve from the onset. The structure of the thesis is provided at the end of this chapter.

1.1 Rationale for the Research

Boxing is a popular sport having featured across almost all Olympic Games (OG) in history. Boxing was established in the modern OG in 1904 in St. Louis, USA, featuring seven men's weight categories. This Olympic participation continues with a confirmed presence at the upcoming 2024 edition in Paris, France, across thirteen weight categories; seven men and six women (International Olympic Committee, 2023). The sport of boxing was well recorded in ancient Greek manuscripts and pottery, with injuries from participants described around 400 BC (Chagnon, 1988; Grammaticos and Diamantis, 2008). To protect the hands, Greek boxers bandaged them in soft leather thongs or Cestus. Over several centuries, the Cestus developed from the soft leather bandages, used in ancient Greece, to hard leather materials in Roman times (Figure 1). The material and style of hand-wrist bandaging evolved to better protect this region, while meeting spectacle requirements of the audience.

Figure 1.1: Historical boxing hand-wrist bandaging techniques with; a) Greek style, and b, c) Roman style.

In the seventeenth- and eighteenth- century boxing evolved as a sport with the development of rules and regulations (Boulton, 2011). The Queensbury rules were introduced in 1865, and in 1880 the sport split into two distinct styles; amateur and professional boxing. These two styles have their own distinct rules and regulations (International Boxing Association, 2023; British Boxing Board of Control, 2021; Boddy, 2008). Bandaging techniques, to protect the hand-wrist from injuries (ligament sprains/tears and bone contusions/fractures), have evolved with regulations defining what is allowed during competition (British Boxing Board of Control, 2021; Gems, 2014; International Boxing Association, 2023).

Compared to amateur boxing, professional boxing allows for more hand-wrist protection in competition. Some amateur boxing competitions only allow the use of cotton material for hand-wrist bandaging, whilst other formats allow the use of rigid tape (International Boxing Association, 2023). Conversely, rigid tape is allowed in all professional style boxing (British Boxing Board of Control, 2021). Rigid tape is used in sports as prevention or post-injury management aiming to increase support at joints (Kim et al., 2020; Purcell et al., 2009; Sato et al., 2019). No rationale is available for this difference in protection between amateur and professional boxers. Far more amateur boxers compete at a tournament compared to a professional show. An explanation for this difference is therefore likely due to lowering of economic costs and ease of application in the materials required for hand-wrist protection in the amateurs. In amateur boxers, the local organising committee provides bandages to boxers. Conversely, professional boxers are expected to source their own materials, in accordance with the regulations. However, professional boxers, when compared to amateur boxers, get paid.

In a review of thirteen boxing studies, conducted between 1959 and 2009, it was observed that the hand-wrist was the most injured region accounting for 16% of all injuries (Loosemore and Beardsley, 2015). In this review, there was considerable variability in the proportion of hand injury rates between the studies (range: 7-100%). This variability, although not discussed in this review, can be explained by the differences in gloves between amateur and professional styles of boxing. During the period covered in these studies, the glove size was smaller 8oz (227g) in the professional style compared to 10oz (284g) in the amateur style. However, hand-wrist injury rates were substantially more variable in the amateur style (hand ranges: 7-100%; wrist ranges: 9-49%), than in the professional style (hand ranges: 79-89%; wrist ranges: 0-0%). During the period these studies were conducted, there was no restriction on the amount of hand-wrist bandage and tape allowed in the professional style, if the bandaged hand fitted into the boxing glove. During the same period, in the amateur stye hand-wrist bandages were limited to 2.5 metres of cotton bandage per hand. Further in amateur style tournaments, including the OG, boxers can compete up to five times within two weeks. In professional events, there is at least a few weeks between competitive bouts, and sometimes considerably more.

Rule changes in the international amateur style of boxing (International Boxing Association, 2023), intended to reduce injuries, increased the bandaging length allowance from 2.5 to 4.5 metres. Despite such rule changes, the incidence of injury in the hand-wrist complex in amateur boxing remains high. Between 2005 to 2012, it was observed that hand-wrist injuries for the Great Britain (GB) squad accounted for about a third of all injuries in training and competition (Loosemore, et al., 2017). Further, total days lost to training and overall duration were significantly greater for the hand-wrist than any other body part. When rigid taping was combined with traditional bandaging (i.e., bandage only), as part of training strategies in the GB boxing programme, an improvement in training availability in hand-wrist injuries was anecdotally observed. At the Rio 2016 OG, amateur boxers were allowed a professional style bandaging technique which includes the use of rigid tape. Although injuries still occurred at the hand-wrist, it was anecdotally observed that severity (i.e., days lost due to injury) of carpometacarpal (CMC) injuries was reduced when compared to other tournament formats restricting the use of rigid tape.

Application of rigid tape to bandage has been anecdotally observed through clinical practice as influential towards injury rate reduction, as well as improving training and competition availability when injuries did occur. In boxing, the CMC region of the hand has been identified as the most common injury, incurring the highest time loss from training (Loosemore et al., 2017; 2015a). Noble (1987), stated that if hyperflexion of the wrist occurred on impact in boxing it would injure the CMC joint of the hand. Through video analysis post injury at GB Boxing and discussing the injury mechanism directly with the injured boxers, it appears the amount of wrist motion occurring, specifically flexion, is likely an important factor towards hand-wrist injuries. Flexion, as a mechanism for CMC injuries in boxing, can be further supported through clinical orthopaedic testing and surgical procedures used post-injury (Matharu et al., 2022a).

It is therefore proposed that reducing wrist motion, specifically flexion, on impact can be an important variable towards hand-wrist injury prevention in boxing. While studies investigating the kinematics of boxing have provided information on the range of motion (ROM) occurring at the shoulder and elbow joints (Piorkowski et al 2011; Whiting, Gregor, and Finerman, 1988), no study has investigated wrist motion occurring on impact in boxing. Kinematics is a term used to define the time course of changes in position and orientation of body segments and the geometry of motion in terms of displacements, velocities, and accelerations without considering the kinetics behind the generation of the motion (Arslan et al., 2019).

1.2 Aims and Objectives

The aim of this programme of research was to develop a methodology to quantify wrist motion on impact in boxers and evaluate the effects of bandaging techniques on wrist motion during different shot types. This will be achieved through the following objectives:

1. To review existing research combining knowledge acquired through clinical/in-field observations in boxing.
2. To review existing methodologies used to measure wrist kinematics, identifying gaps, developing, and piloting of potential novel approaches.
3. To determine the validity and repeatability of a system to measure wrist kinematics on impact in boxing.
4. To quantify wrist motion on impact during different shot types in boxing.
5. To identify the effect of different bandaging techniques on wrist motion on impact during different shot types.

1.3 Structure of the Thesis

All the Chapters in this programme of research are aimed at fulfilling objectives 1. and 2. Chapter 3, which describes the methodologies used in the studies conducted as part of this programme of research, is aimed at part fulfilling objective 2. Objectives 3, 4 and 5 will be respectively covered in Chapters 4, 5 and 6. These chapters are based on three studies (Gatt, Allen and Wheat, 2023; 2021, 2020), edited for this monograph style, published over the course of the programme of research. Finally, all the objectives and overall results of the programme of research, together with a reflective piece, will be discussed in Chapter 7.

2.0 Literature Review

2.1 Introduction

This chapter reviews the relevant literature in six sections. Section 2.2 outlines the anatomy of the hand-wrist relevant to the studies conducted. Section 2.3 provides an understanding of wrist motion, which is crucial towards the hypotheses generated and results in the studies conducted, described in more detail in Chapters 4 to 6. Section 2.4 discusses the anatomical interactions required to create joint stability at the wrist. This section provides insight into the discussion on dynamic control provided in Chapters 6 and 7. Section 2.5 provides an in-depth understanding of injuries occurring at the hand-wrist, specifically the anatomical regions linked to wrist motion, and therefore the overall approach of the studies conducted. Section 2.6 discusses the role of bandaging at the hand-wrist region towards joint stability and injury prevention. This section supports the rationale for conducting the study in Chapter 6, and overall concept for this programme of research. Section 2.7 forms the final part of this chapter, exploring different methodologies available for measuring wrist kinematics, providing a validation for the approach discussed in Chapter 3.

2.2 Relevant Hand-Wrist Anatomy

The hand-wrist region is made of 29 bones; 14 Phalanges, 5 Metacarpals, 8 Carpals, 1 Radius and 1 Ulna. Of relevance to this programme of research are the wrist and CMC joints consisting of 15 bones (5 Metacarpals, 8 Carpals, Radius and Ulna) (Figure 2.1)

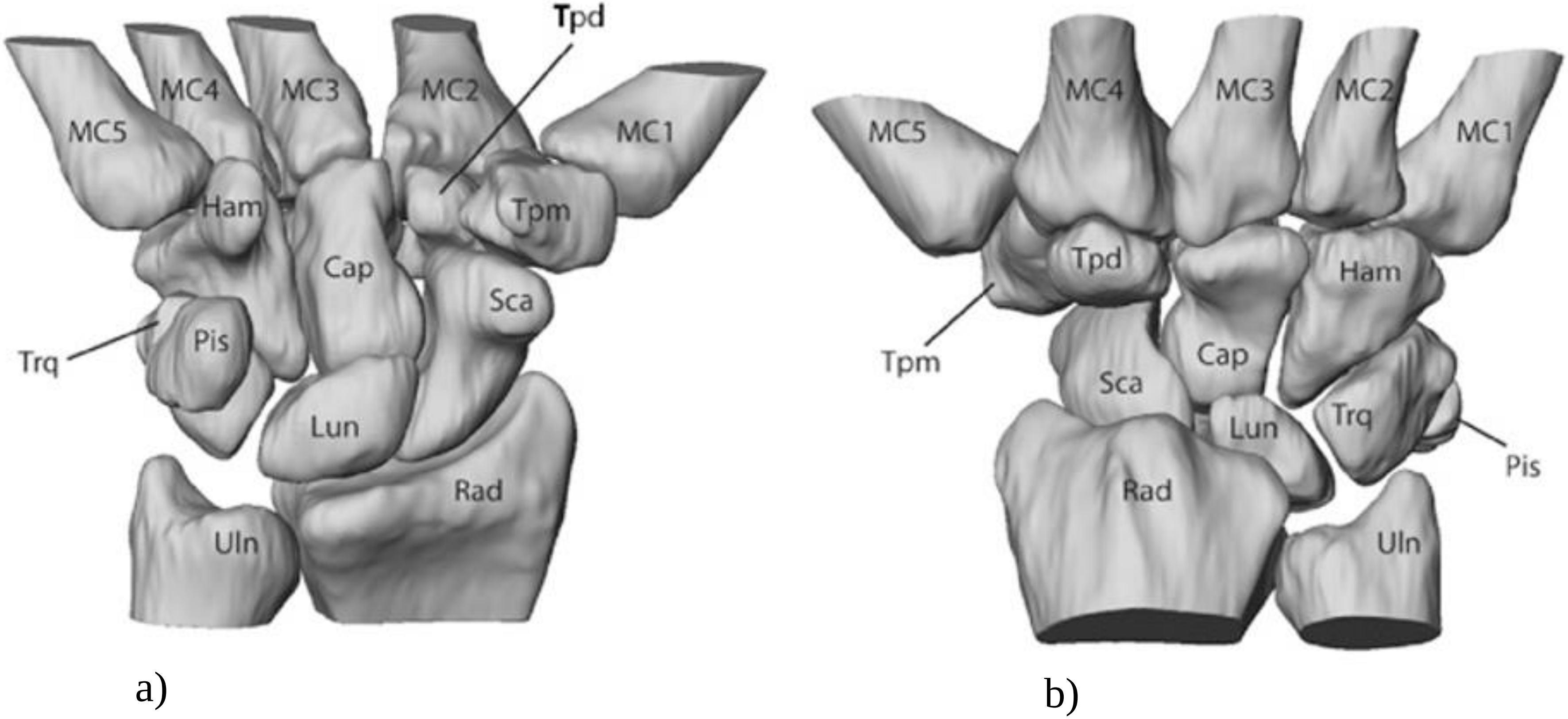


Figure 2.1: Bone anatomy of the wrist and CMC joints with a) volar and b) dorsal views of the bones from a right hand-wrist. From radial to ulnar direction, Metacarpal bones are; MC1 to MC5, the distal carpal bones are; Trapezium (Tpm), Trapezoid (Tpd), Capitate (Cap), Hamate (Ham), the proximal carpal bones are; Scaphoid (Sca), Lunate (Lun), Triquetrum (Trq), Pisiform (Pis), and the forearm bones are; Radius (Rad), Ulna (Uln). *Figure source from Moore et al. (2007).*

The wrist has two articulations; the midcarpal (MiC) joint formed between the distal and proximal row of carpal bones, and the radiocarpal (RC) joint formed between the distal radius and the proximal row of carpal bones (except the pisiform). The pisiform bone is not involved in the direct mechanics of the wrist. This bone does however provide a mechanical advantage to the Flexor Carpi Ulnaris (FCU) muscle, whilst providing an attachment for the ulnar collateral ligament of the wrist. Both the RC and MiC joints contribute to the biplanar motions of the wrist (Figure 2.2); flexion (FLEX) to extension (EXT) (sagittal plane motions), and radial deviation (RD) to ulnar deviation (UD) (frontal plane motions).

The RC joint is the articulation between the radius, and the scaphoid and lunate bones. There is a small area of contact with the triquetrum bone, observed in kinematic studies using biomechanical modelling through magnetic resonance imaging (MRI) (Goto et al., 2005; Moritomo et al., 2004). The wrist joint is typically described as an ellipsoid (or condyloid) joint allowing two planes of motion in both sagittal and frontal planes (Goto et al., 2005; Moritomo et al., 2004). Some wrist rotation around a transverse plane is also available (Goto et al., 2005; Moritomo et al., 2004). The Ulna is not involved in wrist mechanics, however the structures that attach to it, Triangular Fibrocartilage Complex (i.e., triangular fibrocartilage discus, radioulnar ligaments, and the ulnocarpal ligaments), are important towards wrist stability (Zhu et al., 2018). The ulna can glide on the discus, found between the ulnar and proximal carpal bones, in pronation and supination whilst not influencing carpal movements (King et al., 1986).

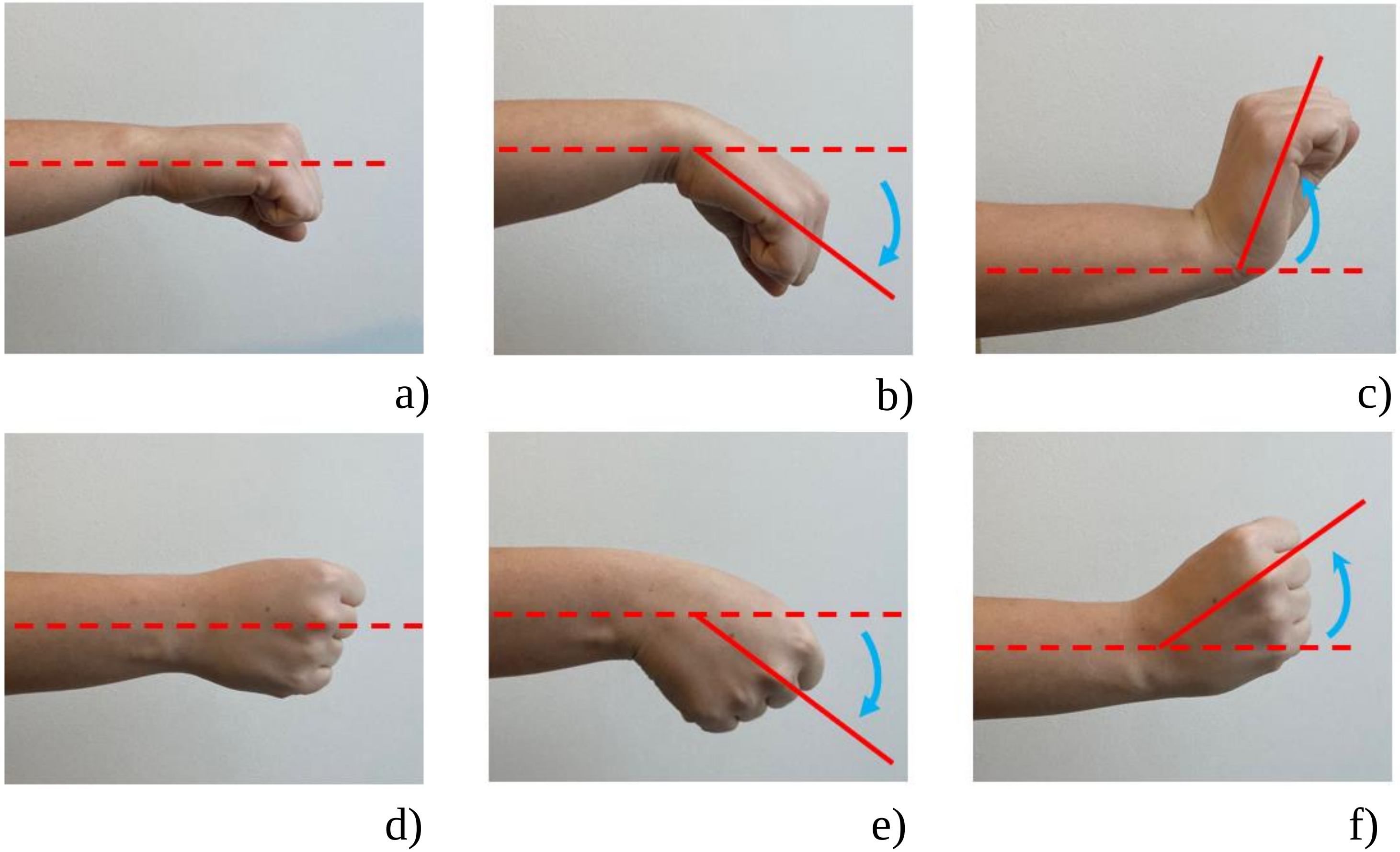


Figure 2.2: Wrist motions with a closed fist depicted with the forearm in a full pronated (palm down) position with a side view showing; a) neutral, b) FLEX and c) EXT, and an aerial view showing; d) neutral, e) UD and f) RD. Dashed red line indicating neutral or zero joint position, solid red line indicating end position of joint motion relative to dashed line, and blue arrow depicting arc and direction of motion

The MiC joint is formed by contact of the four distal carpal bones and the more proximal three carpal bones (pisiform only articulates with triquetrum so is not considered part of the MiC joint). The MiC joint is a complex joint that is responsible for facilitating wrist motion and force transmission between the hand and forearm (Fischer et al., 2021; Garg et al., 2014; Goto et al., 2005; Leventhal et al., 2010; Li et al., 2005; Moritomo et al., 2004; Nadeem et al., 2022). The mechanics of the MiC joint involve the coordinated movement of multiple bones, ligaments, and muscles (Eschweiler et al., 2022; Goto et al., 2005; Moritomo et al., 2004).

During wrist FLEX (bending the wrist towards the palm), the proximal row of carpal bones moves in a dorsal direction whilst the distal row moves in a palmar (volar) direction. During wrist EXT (bending the wrist back), the opposite occurs. During wrist RD (wrist moves towards the thumb), the proximal row of carpal bones moves in UD (wrist moves towards the little finger), while the distal row moves in RD. During wrist UD, the opposite occurs. Additionally, the ligaments surrounding the MiC joint play an important role in stabilising the joint and facilitating its motion. The ligaments on the dorsal and palmar aspects of the joint provide stability during wrist FLEX and EXT respectively, whilst the ligaments on the ulnar and radial sides provide stability during wrist UD and RD.

The CMC joints are formed by each of the five metacarpal joints and their corresponding distal carpal row bone. The metacarpal (MC) bones, from radial to ulnar direction are numbered (MC1 to MC5). The articulations for each CMC joint, radial to ulnar direction are; MC1 with trapezium, MC2 with trapezoid, MC3 with capitate, and both MC4 and MC5 with hamate (Figure 2.1). The CMC joints are enclosed by a joint capsule. There is little sagittal movement (5 degrees) occurring at the index and middle finger CMC joints due to an interlocking bony architecture (Matharu et al., 2022a; Morgan and Carrier, 2013). The index finger CMC joint articulates with the V-shaped facet of the trapezium, and smaller facets for the capitate and trapezoid (Morgan and Carrier, 2013). The middle finger metacarpal interlocks radially with the index MC and articulates with a V-shaped facet of the capitate. The ring and little finger CMC joints articulate against two flatter facets on the hamate compared to the index and middle finger. The shape of the CMC joints allows for more sagittal motion (30 degrees) at the ring and little finger, than the index and middle finger CMC joints (Matharu et al., 2022a; Nazarian et al, 2014). CMC joint motion therefore increases from radial to ulnar sides of the hand, as the articular surfaces become less curved. The dorsal ligaments limit volar directed, or FLEX, movement in the sagittal plane for all CMC joints. These dorsal ligaments are commonly damaged with CMC injuries, suggesting that forced FLEX is the mechanism of injury occurring on impact (Matharu et al., 2022a; Nazarian et al., 2014).

2.3 Wrist Motion

Wrist motion refers to the movement of the wrist joint, which connects the forearm to the hand. The wrist joint is a complex joint that allows for various movements. Wrist motion is essential for many daily activities and sports. The following sections will describe this motion in more detail.

2.3.1 An Overview of Wrist Motion

The wrist is a two degree of freedom (DoF) universal joint, with the motions occurring about two axes; FLEX-EXT occurring about the frontal axis (sagittal plane), and RD-

UD occurring about the sagittal axis (frontal plane) (Eschweiler et al., 2022). Mapping wrist motions could be performed using an illustrative face of a clock (Figure 2.3). If the right hand was positioned in a palm down position, EXT towards FLEX occurs from 12:00 to 6:00 o'clock. (Figure 2.3). UD towards RD occurs from 9:00 to 3:00 o'clock (Figure 2.3). These motions occur as a combination of contributions from both RC and MiC joints (Eschweiler et al., 2022). The functional ROM at the wrist can vary and is dependent on the specific tasks being performed (Palmer et al., 1985; Ryu, et al., 1991). Additionally, some individuals may have greater or lesser ROM due to variations in joint structure or other anatomical factors. RD, although typically less than the range of UD, is important as it creates the stable position or closed pack which stabilises the wrist (Palmer et al., 1985; Ryu et al., 1991). This stable position occurring in RD, which couples in EXT, is essential for certain tasks in sport like serving in tennis or adopting a handstand in gymnastics. This combined position of RD with EXT is a component of the dart throwing motion (DTM) (Figure 2.3), which will be discussed in more detail in the next section.

Normative values for ROM have been provided in different studies, although values have been measured using an open hand approach (Alford, 2021; Kim, et al., 2014). Wrist motion, however, can likely differ when using an open rather than a closed hand. Although this difference has not been reported in the literature, more motion is typically observed clinically amongst practitioners at the wrist for FLEX with an open than closed hand, and for EXT with a closed than open hand. Open and closed hand, for FLEX and EXT respectively, are also the positions of choice for stretching the forearm, as provided regularly by healthcare practitioners. Further, a common clinical

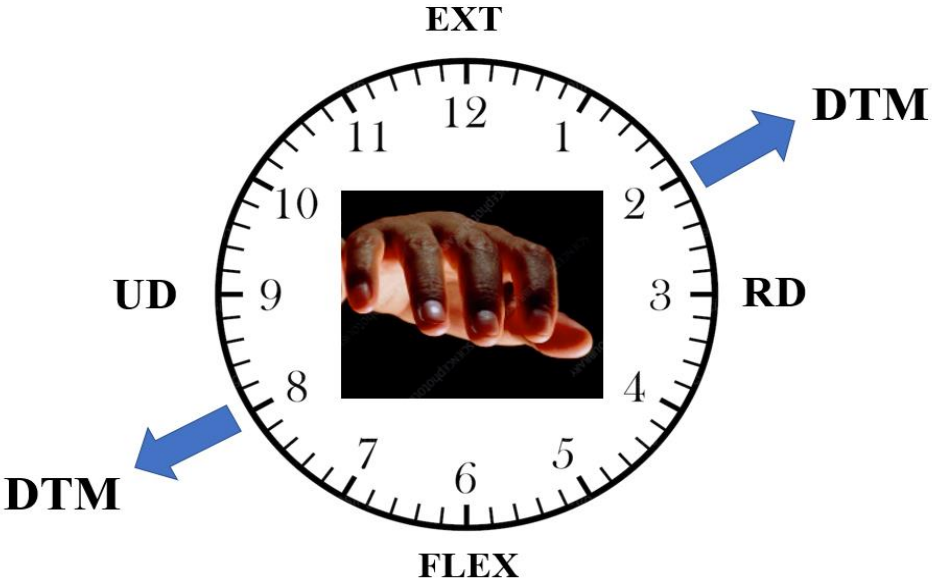


Figure 2.3: Wrist motion depicted using the face of a clock A right wrist showing motions of FLEX-EXT at 6:00-12:00, and UD-RD at 9:00-3:00. The DTM direction is also included showing; EXT-RD to FLEX-UD running approximately from 2:00 to 8:00.

for FLEX and EXT respectively, are also the positions of choice for stretching the forearm, as provided regularly by healthcare practitioners. Finally, a common clinical test used for provoking pain with lateral elbow tendinopathy is performed by inducing a stretch on the dorsal musculature of the forearm with a closed hand (Cohen and da Rocha Motta Filho, 2012). This test forces the closed hand of the patient into FLEX and then extends the elbow, whilst the forearm is maintained in a pronated position (Cohen and da Rocha Motta Filho, 2012). This difference between open and closed hand position, in wrist ROM, is of relevance to boxing as on impact the hand is typically maintained in a closed hand position. A closed hand position, if flexed, would stretch the anatomical structures (skin, underlying fascia, ligaments, and joint capsule) on the dorsum of the hand, wrist. and forearm A similar effect is typically observed, at the anatomical structures on the volar side, if an open hand position is extended. Ulnar and radial aspects do not appear to demonstrate any differences between open and closed hand positions.

2.3.2 Dart Throwing Motion

Wrist motion is described as uniaxial motions occurring in either FLEX-EXT or RD-UD. Kinematic studies, however, describe a biplanar coupled motion occurring naturally in daily activities and sports, described as DTM of the wrist (Fischer et al., 2021; Goto et al., 2005; Leventhal et al., 2010; Li et al., 2005; Moritomo et al., 2004; Sweeney et al., 2012; Wolfe et al., 2006), rather than separate uniaxial motions. The DTM involves an arc of motion from combined RD-EXT to UD-FLEX (Figures 2.3 to 2.5). For example, it was observed that during the downswing in golf, both wrists experienced FLEX and UD (Sweeney et al., 2012). The DTM is described as the most stable and controllable arc of motion, representing the functional plane of wrist motion for most occupational and avocational activities (Fischer et al., 2021; Goto et al., 2005; Leventhal et al., 2010; Li et al., 2005; Moritomo et al., 2004; Sweeney et al., 2012; Wolfe et al., 2006).

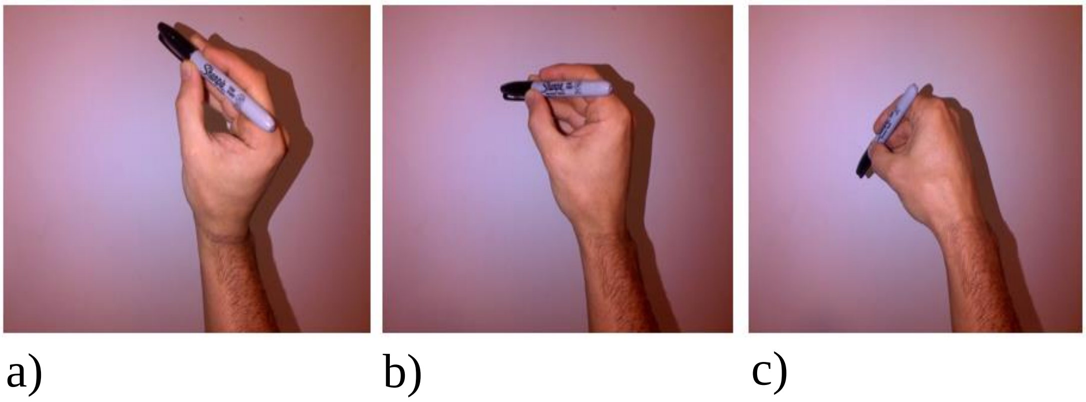


Figure 2.4: DTM occurring at the wrist with; a) EXT-RD, b) Neutral, and c) FLEX-UD

The DTM is probably best explained due to the anatomy of the MiC joint. The MiC joint may have the most complex joint shape in the human body (Garg et al., 2014; Li, et al., 2005; Moritomo et al., 2004). Although the MiC joint is classed as one articulation, it could be divided into two distinct articulations: the scaphotrapeziotrapezoid (STT) joint and the scapholunotriquetrum-capitate-hamate (SLT-CH) joint (Moritomo et al., 2004). The STT joint is convex proximally whereas the SLT-CH joint is concave (Moritomo et al., 2004). Through 3D analysis of the wrist, based on MRI sequencing, it appears that most of the joint surface of the MiC joint forms an ovoid whose major axis runs obliquely from radiopalmar to ulnodorsal (Figure 2.5). The STT joint contacts the distal and radial parts of the ovoid, whilst the SLT-CH joint contacts the MiC joint allowing for motion to occur in an oblique plane with wrist radiodorsal-to-ulnopalmar rotation.

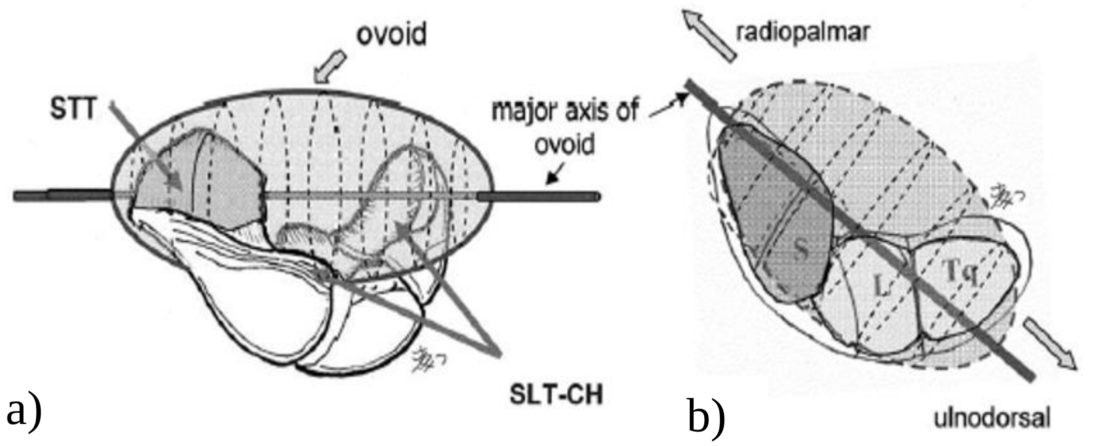


Figure 2.5: MiC joint showing axis of rotation. Views of the proximal row and an ovoid; a) Radio-dorsal and b) distal. Most of the joint surfaces of the MiC joint contact with the imaginary ovoid, whose major axis runs obliquely from radiopalmar to ulnodorsal. Scaphoid (S), Lunate (L), Triquetrum (Tq). *Figure source from Moritomo et al. (2004).*

2.3.3 Musculature Involved in Wrist Motion

Thirty-nine muscles act at the hand-wrist. Most of the muscles originating outside the hand are termed extrinsic (enter the hand as tendons not to make the hand bulky). Wrist Flexors (FCU, Palmaris Longus and Flexor Carpi Radialis) originate at the medial epicondyle of the elbow and become tendons halfway along the forearm. FCU is described as the strongest of the muscles acting at the wrist (Lung and Siwiec, 2023). This strength is important since FCU is described as performing FLEX and UD (Lung and Siwiec, 2023), which can be explained by its anatomical attachments at the wrist (Figure 2.6). FLEX combined with UD has been described before as occurring in the DTM, highlighting the importance of this muscle during motions occurring in daily activities and sports.

Located anatomically obliquely, opposite to FCU (volar-ulnar position), are two wrist Extensors; Extensor Carpi Radialis Longus (ECRL) and Extensor Carpi Radialis Brevis (ECRB) (dorsal-radial position) (Figure 2.6). These muscles have been described to create EXT and RD of the wrist, whilst also assisting FLEX of the elbow with a fixed wrist (Lung and Siwiec, 2023). EXT occurs as a coupled movement occurring with RD (Moritomo et al., 2004; Wolfe et al., 2006). Considering the DTM, the role of ECRL and ECRB, in combination with FCU, would therefore be of importance in controlling wrist motion. The role, particularly of ECRL and ECRB, towards wrist stability and injuries at the CMC joints will be discussed further in the next sections.

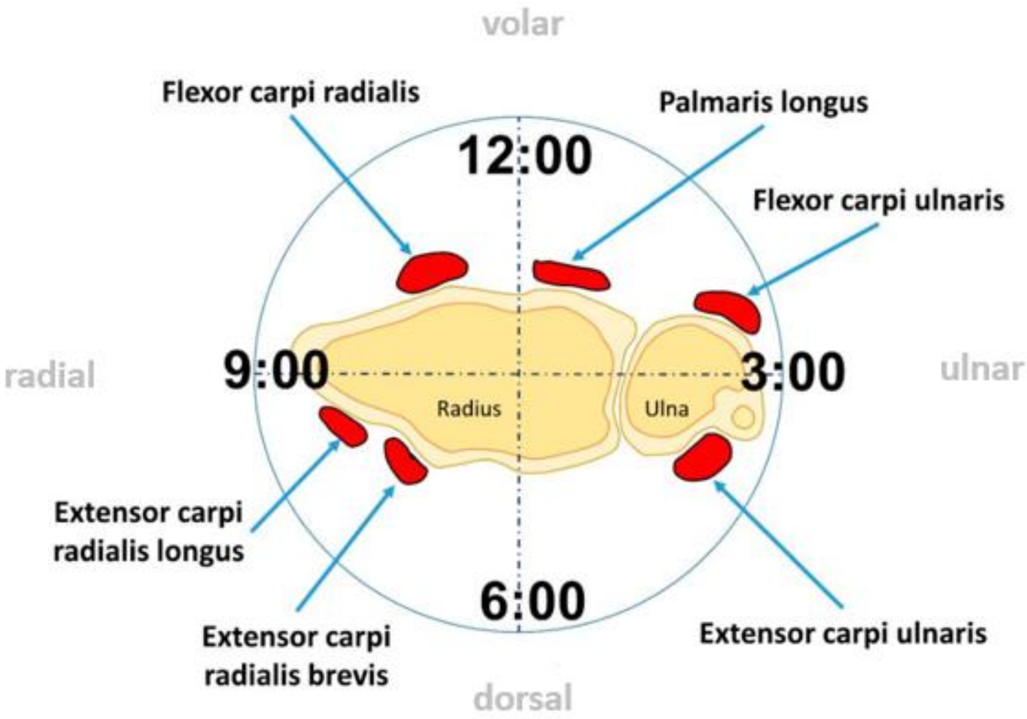


Figure 2.6: Anatomical position for the distal attachments of the muscles acting at the wrist. Wrist muscles position from a distal to proximal view. *Figure source from Eschweiler et al. (2022).*

2.4 Joint Stability at the Wrist

Joint stability refers to the resistance offered by various tissues that surround a joint (Panjabi, 1992). Several subsystems ensure the stability of a joint. Stability was first described in the spine as being an interaction between the passive, active and neural subsystems (Panjabi, 1992). Although an understanding of the interaction of these systems is still not fully understood in the wrist, different components have been considered (Hagert, Forsgren and Ljung, 2005; Linscheid and Dobyns, 2002; Mayfield, Johnson and Kilcoyne, 1976; Salva-Coll et al., 2011).

Passive or static stability has been described as provided by an interaction of extrinsic and intrinsic ligament, and the morphology of the articular surfaces of the joints acting at the wrist (Linscheid and Dobyns, 2002). The role of ligaments to create static stability is well documented in the literature. In 1976, Mayfield and colleagues examined 19 injuries created mechanically on cadaveric wrists (Mayfield et al., 1976). In their study they assessed six ligaments in the wrist and showed their role in stabilising the carpal bones. Hagert et al (2005) also performed a study to analyse human wrist ligaments. In this study they observed ligaments with and without innervations. The authors proposed that ligaments without innervation would function as structures of passive restraint, as supported by earlier studies, whereas ligaments with innervations would additionally provide proprioceptive information. This study therefore provided initial evidence on how ligaments at the wrist could be linked to active or dynamic stability. The authors further commented that wrist ligament injuries should therefore be regarded as a disruption not only of the intrinsic carpal kinematics, but also proprioception of the entire wrist joint.

The term proprioception has been used since the early 20th century to indicate the sensory perception and subsequent motor control of posture, balance, audio-visual and motor coordination, and joint stability (Hagert, 2010). In 1958, Palmer and colleagues were the first to show the existence of reflexes between ligaments in a joint and the muscles acting on that joint (Palmer et al., 1985). In this study, the authors observed the effect of direct tension on the medial collateral ligament of the knee, resulting in a fast reflex response in periarticular muscles interpreted as joint protective reflexes. Since then, similar studies on joint ligament-muscular reflexes in humans have been documented in the knee, ankle, shoulder, elbow, and wrist joint (Diederichsen, et al., 2004; Freeman and Wyke, 1967; Hagert et al., 2009; Johansson, Sjölander and Sojka, 1991; Solomonow, 2006).

In an *in vivo* study on proprioception at the wrist, electrical stimulation of the dorsal scapholunate interosseous ligament resulted in excitatory or inhibitory activation of wrist flexor and extensor muscles, occurring at specific time intervals (Hagert et al., 2009). This study provided good evidence of the proprioceptive reflexes between wrist ligaments and the forearm muscles. These reflexes were consistently seen in the antagonist muscles of each wrist position, indicating a possible joint protective function. From other joints, it is well recognized that a co-contraction of agonist and antagonist muscles around a joint will create a general joint stiffness, thereby effectively reducing the risk of joint damage (Johansson, 1991; Myers and Lephart, 2000).

The afferent signals from primarily muscle spindles and cutaneous receptors are appreciated consciously and described as kinaesthesia (the perception of active and passive motion) and joint position sense (the ability of a person to identify the position of a limb in space) (Aydin et al., 2001; Proske, 2006). Joint position sense (JPS) is an important aspect of proprioception. An intact JPS has been shown to be necessary for normal muscle coordination and timing, evidenced when active muscle forces are required for the stability of the joint (Blasier, Carpenter and Huston, 1994). JPS is described as provided by the adapting musculotendinous (muscle spindles and Golgi tendon organs) and capsule-ligamentous (Ruffini, and Golgi tendon organ like endings) mechanoreceptors, which are stimulated by deformation of larger anatomical structures (i.e., joints) (Janwantanakul et al, 2001).

In proprioception training, JPS is defined as the ability to accurately reproduce a specific joint angle. This training can be done either passively or actively, with visual cues or blinded. Passive JPS is when the therapist moves a joint, like the wrist, and the patient signals when the target position is reached. Active JPS is when the patient moves a joint actively to the predetermined target position. Table 2.1 outlines some studies on JPS which have been performed in different anatomical locations, including the wrist.

When discussing proprioception, it is also important to consider the cerebellum, the region of the brain that plays the role of integration of sensory perception, and motor control. This structure is therefore the primary site for the generation of unconscious proprioception, which involves the neuromuscular control of a joint through reflex regulations as well as pre-programming of muscle stiffness in anticipation of coming motor actions (Johansson et al., 1991). This feed-forward anticipatory control of muscles around a joint is responsible for unconsciously retaining an adequate posture and maintaining joint stability and equilibrium (Sjölander, Johansson, and Djupsjöbacka, 2002). This feed-forward anticipatory control of muscles around a joint would therefore be expected to have a role at controlling stability of joints, namely the wrist, of a boxer on impact, together with other components linked to positioning and balance. To fully understand joint stability, it is therefore essential to understand the contribution from muscle spindles, cutaneous receptors, and joint afferents. These contributions undoubtedly constitute the essence of proprioception as related to sensorimotor joint control or joint stability.

Table 2.1: JPS assessment techniques.

AUTHORS	JOINT	TYPE OF STUDY	TYPE OF SYSTEM UTILISED	CONCLUSION FROM STUDY/COMMENTS
(Gay et al., 2010)	Wrist	8 participants had their right upper extremity tested for active reproduction and passive reproduction using a custom-made motion tracking system.	Custom made motion tracking system (Manipulandum) & two electromagnetic sensors (Flock of Birds) were attached to the dorsal forearm and the middle of the dorsal aspect of the third metacarpal to measure wrist flexion/extension.	Repeatability coefficient is better, both in active and passive condition, when the sensors are placed on the Manipulandum rather than directly on the skin
(Herrington, Horsley and Rolf, 2010)	Shoulder	15 asymptomatic professional rugby union players, 15 previously injured professional rugby, 15 asymptomatic matched non-rugby playing controls had their JPS assessed.	JPS assessed using two criterion angles in the 90^{o} shoulder abduction position (45 and 80 external rotation). Passive setting of the index angle, followed by active reproduction of that angle in supine on a couch.	This study showed rugby players to have better JPS than controls, indicating JPS might not be related to injury risk.
(Lönn et al., 2000)	Shoulder	16 participants performed four testing procedures consisting of different types of limb displacement (active, passive, and passive during antagonist muscle contraction).	The rig was equipped with a DC-servomotor controlled by personal computer (PC). A receiver attached beneath the apparatus and a stationary electromagnetic transmitter (FASTRAK) were used to monitor orientation of the rig.	Lower repositioning errors occurred with active displacement procedures compared with passive, and with the intermediate starting position compared with the extreme. Target position, however, had no effect on repositioning errors.
(Yalcin et al., 2012)	Ankle	26 individuals with flexible flatfoot and 27 healthy control subjects were evaluated. Passive reproduction of joint position tests enabled the measurement of a subject's position sense.	Absolute error (in degrees) for passive reproduction of joint position tests and peak isokinetic strength of ankle muscles for eversion and inversion were tested using the Biodex isokinetic dynamometer.	For individuals with flatfoot, passive reproduction of joint position error scores in eversion were significantly higher for the dominant side compared with the control group

It appears that joint stability is provided by the shape of the bones and the ligaments that support them. Crucially, however, are the muscles that cross a joint controlled by a sophisticated proprioceptive system. At the wrist, as mentioned, there are ligaments which depending on their position will provide afferent stimuli (proprioceptive input). This input in turn will activate or inhibit muscles acting at the wrist. This process is termed active stability or dynamic control, which is also known to occur in other joints (Herrington et al., 2010; Janwantanakul et al., 2001; Lönn et al., 2000; Yalcin et al., 2012). Boxers are instructed to make a fist before impact, which appears important as co-contraction of the muscles acting at the wrist is required to create stability (i.e., joint stiffness) (Holmes, Tat and Keir, 2015; Salva-Coll et al., 2011).

Maximal grip strength in normal healthy individuals has been observed to occur at 30 to 35° of wrist extension, with a substantial reduction in grip strength when deviation falls outside this range (Lee and Sechachalam, 2016; O'Driscoll et al., 1992). Since wrist extension is predominantly performed by the actions of ECRL and ECRB muscles, it appears that limiting the opposite action of these muscles, ulnoflexion, could influence grip strength and therefore wrist stability on impact in boxing. Wrist FLEX, as mentioned, is clinically observed to occur more with an open than a closed hand, with the latter being the position of boxers' hand on impact. Although this can likely provide a position for better dynamic control, through improved muscle co-contraction (Holmes, Tat and Keir, 2015; Salva-Coll et al., 2011), it also provides less passive motion available at the wrist. A balance between passive restriction and muscle stiffness is likely occurring at the wrist on impact in boxing to create stability. This balance between passive and active components of wrist stability will be discussed further in Chapter 6.

2.5 Hand-Wrist Injuries in Boxing

A sports injury has been defined as tissue damage or other derangement of normal physical function due to participation in sports, resulting from rapid or repetitive transfer of kinetic energy (International Olympic Committee Injury and Illness Epidemiology Consensus Group, 2020). An injury may be classed as an acute episode; resulting from a near-instantaneous exchange of large quantities of kinetic energy (e.g., as in a collision between athletes), overuse episode; gradual accumulation of low-energy transfer over time (e.g., as in the bone stress injury example) or acute episode due to overuse; a combination of both acute and overuse mechanisms (e.g., repetitive training regime resulting in ligament weakness that then manifests itself acutely as a tear from acceleration forces applied during a single event) (International Olympic Committee Injury and Illness Epidemiology Consensus Group, 2020). Understanding hand-wrist injuries in boxing is therefore necessary to better inform current and future prevention and management strategies.

The hand-wrist region is complex, which leaves many perplexed on how to manage injuries when they occur in various sports and activities of daily living. Comparable to other anatomical regions highlighted in other sports (e.g., shoulders in baseball, hamstrings in football players), it is critical to consider appropriate factors linked to these injuries. It has been described that to establish a complete understanding of the causes of injury, the mechanisms by which they occur must also be identified (Bahr and Holme, 2003). Simply, sports injuries result from a complex interaction of multiple risk factors and events of which only a fraction have been identified in sports. In boxing, there is still limited understanding of these risk factors, especially around hand-wrist injuries.

Risk factors are traditionally divided into two main categories: internal (or intrinsic) athlete related risk factors, and external (or extrinsic) environmental risk factors (van Mechelen, Hlobil and Kemper, 1992; Williams, 1971). Overall, a combination of intrinsic and extrinsic factors can contribute to hand-wrist injuries in boxing. Table 2.2 has been created to provide factors likely contributing to injuries at the hand-wrist in boxing, based on clinical experience, injury audit information and available literature (Gatt, 2021; Gatt et al., 2018; Gatt, 2018; Loosemore et al., 2017; Matharu et al., 2022a; 2022b;). In boxing, high velocities and forces occurring when an athlete throws and lands a shot need to be accounted for, as well as the intended target which can alter between training and competition environments. Some of these factors are discussed in this chapter.

Table 2.2: Intrinsic and Extrinsic Factors for Hand-Wrist Injuries.

Intrinsic	Extrinsic
Hand Size & Shape	Hand Bandaging (materials/technique)
Proprioception	Knuckle Pads
Strength	Gloves (size, quality/wear and tear)
Mobility/Flexibility	Pad Training (coaching style)
Impact Forces	Bags (materials/weight)
Fatigue	Opponent (Experience)
Experience	Training Load (intensity, volume, and frequency)
Boxing Stance	Social Commitments (impact on recovery)
Previous Injury (local)	
Previous Injury (whole body)	
Athlete Beliefs	

2.5.1 Prevalence, Incidence and Location

The prevalence of hand-wrist injuries is common in sport medicine and accounts for about a quarter of all sporting injuries (Stögner et al., 2020). Sports-related hand injuries, treated at an accredited Hand Trauma Centre in Germany, were reviewed retrospectively over a 5-year period (Stögner et al., 2020). In this study, hand injuries in boxing only accounted for 3% of 364 hand injuries recorded across 42 sports. Compared to cycling (28%) and Football (18%), this incidence appeared rather low. However, no comparison was made between hand and other injuries occurring in the rest of the body within the same sport. Further, the number of participants could have varied between sports, with the data provided not normalised to population. The rate of injury reported in this study are therefore the cases presenting at this centre rather than a true representation of the difference in injury incidence occurring amongst sports.

Another study recorded injuries from 3,984 athletes across 36 sports at the 2018 youth Olympic summer games (Steffen et al., 2020). In this study, hand (n=5) and wrist (n=3) injuries in boxing were observed as the highest number in these locations when compared to all the other sports. Further, hand injuries in boxing were recorded as the highest number amongst other locations in this sport. Conversely, the most common injured locations across all sports were knee, followed by ankle, thigh, lower leg, and shoulder.

Lystad et al. (2020) observed the injury incidence across three consecutive Olympics for the combat sports competing at these events: boxing, judo, taekwondo, and wrestling. Boxing recorded the most injuries across the sports, however, hand and wrist injury incidence was similar across these sports apart for wrist injuries which were absent in wrestling. Conversely to Steffen et al (2020), in boxing the hand-wrist injuries were not the most observed in the UpperLimb region.

In another study, a 5-year injury surveillance was conducted which collected injury data between 2005-2009, providing an epidemiology of elite amateur level boxing injuries (Loosemore et al., 2015a). Injury incidence was higher in the hand region than the rest of the body with 69 injuries (23%) observed out of 297. Following this study, the authors focused their research on hand-wrist injuries in boxing.

A hand-wrist longitudinal prospective study between 2005-2012, presented findings of 172 injuries across 98 boxers (Loosemore et al., 2017). In this study, injuries at the hand-wrist accounted for about 35% of those in training and competition with the CMC region of the hand identified as the most common injury (22%). Although injuries at the hand-wrist do occur in various sports, injuries at the CMC region appear to be specific to combat sports, with high incidence reported in boxing than other non-combat sports (Adkitte et al., 2016; Loosemore et al., 2017; Stögner et al., 2020).

At GB boxing, an internal analysis of the last Olympic cycle (October 2016-September 2021) was performed with 283 (44%) of injuries located in the upper limb region diagnosed to 68 boxers (Saunders, 2022). Hand-wrist injuries displayed a higher frequency (Table 2.3) than other areas of the upper limb (n=181, 63.9%), as expected (Saunders, 2022). The greatest number of injuries sustained were ligament or joint structures (n=145, 51.7%). Each male boxer sustained a higher mean injury rate (n = 3) than female boxers (n = 2). Gender differences will be discussed in Section 2.5.4.

Table 2.3: Number of injuries and mean days lost categorised into anatomical location. *Table source (Saunders, 2022).*

Location	Number of Injuries	Mean Days Lost (SD)
Hand and Wrist	181	49 (79.0)
Shoulder	60	46 (57.9)
Elbow	29	46 (36.0)
Upper Arm	8	30 (25.2)
Forearm	5	32 (52.2)

2.5.2 Type or Diagnosis

Various studies agree that both soft tissue and bone injuries can occur at the hand-wrist region, on impact, with the former more commonly reported than the latter (Loosemore et al., 2017; 2015; Noble, 1986). Melone, Polatsch and Beldner (2009) describe carpometacarpal (CMC) and metacarpal phalangeal (MCP), located at the back of the hand and knuckle respectively, as the most common injuries. This information is later confirmed by Loosemore et al (2017) who performed a comprehensive review of injuries occurring in elite amateur British boxers from 2005 to 2012. In this study, most of the injuries reported were ligament type injuries, with other soft tissue type injuries including tendon avulsions and intrinsic muscle strains. CMC joint injuries, at the back of the hand, were identified as the most frequent (n = 37) with the highest proportion (21%). This was followed by finger metacarpal (knuckles) and thumb joint injuries, with a respective frequency (n=27 and 25) and proportion (15.8% and 14.6%). Fractures at the hand (phalanges and metacarpal bones) contributed to 5.4% total.

Noble (1986) observed the injury type at the hand-wrist region for 100 consecutive injuries in 86 professional boxers. 24% of hand injuries involved the second to fifth CMC joints, 23% involved ligament tears of the thumb (a.k.a. skier's thumb), 12% involved damage to the second to fifth MCP joint soft tissues (a.k.a. boxer's knuckle), and 8% involved metacarpal fractures of the second to fifth metacarpals, with the majority of these occurring in the fifth metacarpal (a.k.a. boxer's fracture) (Noble, 1986).

Although both soft tissue and bone type injuries can occur, it is important to consider which injuries impact most on time loss. Fractures at the hand in boxing and across other sports can return to punching activities within 4 weeks, even when surgery is required (Geoghegan et al., 2021). In comparison, soft tissue injuries occurring at the CMC and MCP regions in boxing, which typically result in surgery, will require 5-8 months for return to punching activities (Matharu et al., 2022a; 2022b). Further information on time loss is provided in section 2.5.4

2.5.3 Onset and Classification

When attempting to understand injury epidemiology, it is important to identify differences between training and competition. Further it is useful to classify the chronicity of an injury. Chronicity of an injury can be classified using accepted definitions of new, exacerbation, or recurring (Heneghan et al., 2020; International Olympic Committee Injury and Illness Epidemiology Consensus Group, 2020). A *new* injury can be defined as the first injury caused by participation in a sporting event (training or competition). An *exacerbation* can be defined as an injury with the same diagnosis and location (or bilaterally) <6 months from a new injury. A *recurrence* injury can be defined as occurring >6 months from a new injury (Heneghan et al., 2020; International Olympic Committee Injury and Illness Epidemiology Consensus Group, 2020).

Training (n=184, 63%) has been shown to yield more hand-wrist injuries than competition (n=96, 33%), with a small number (n=13, 4%) attributed to other non-boxing causes (Saunders, 2022). This difference in injury prevalence in training compared to competition, can be explained by a higher exposure to the former as compared to the latter (i.e., boxers spend more time training than competing). In terms of recurrence (6%) and exacerbations (2%), the frequency for these categories were low, with most injuries classified as new (n = 270, 92%). This finding agrees with another study where new (77%) injuries at the hand region were significantly higher than recurrent (23%) (Loosemore et al., 2017).

Although more injuries occur in training than competition, a higher rate of hand-wrist injuries, calculated per 1000 hours of participation, has been observed in competition (183 injuries / 1000 hours) than in training (0.15-0.20 injuries / 1000 hours) (Saunders, 2022). A similar higher rate of occurrence in competition (347 injuries / 1000 hrs) than training (<.0.5 injuries / 1000 hrs) has also been observed in an earlier study (Loosemore et al., 2017). In this study, however, a similar prevalence in the rate of hand injuries was sustained during training (52%) and competition (48%) (Loosemore et al., 2017), as compared to a higher incidence in competition observed by Saunders (2022). The authors did not expect this result given that training time was about 100 times longer than competition (Loosemore et al., 2017). The higher rate of incidence in competition as compared to training from both Loosemore et al (2017) and Saunders

(2022) is likely explained by the differences between these environments, namely the amount of bandaging protection available at the hand-wrist. Only up to 4.5m of cotton bandage is available in competition, compared to training where more material, including the use of rigid tape, is allowed. Bandaging, as discussed further in this chapter, forms an important factor towards injury incidence.

In training, various methods are typically used; bags, pads, and sparring. Boxing bags are typically large and cylindrical, filled with materials like sand or cloth. They are used for practising various punching combinations and footwork, whilst developing physical qualities of precision, speed, power, and general conditioning. Working on bags allows boxers to practise their striking techniques with the resistance offered by the weight of the bag. Pads are used to develop similar physical qualities to training on bags. One main difference is pads are held by coaches, which can also be used to develop defensive manoeuvres.

Sparring is also used to develop similar physical qualities to bags and pads. The main difference to other training methods is it provides a controlled practice fight between two boxers under the supervision of a coach. Sparring allows boxers to apply their skills and techniques in a more realistic and dynamic setting, approximating competition. The shot types thrown in both sparring and competition are the same as those on bags or pads. Considering the high rate of hand-wrist injuries observed in training over competition (Saunders, 2022), and that various studies assessing upper limb kinematics and kinetics in boxing typically use training bags (Dinu and Louis, 2020; Stanley et al., 2018; Whiting, Gregor and Finerman, 1988), it seems appropriate to assess wrist kinematics on a training bag. Such an approach would give an appropriate methodology to provide clinical meaningfulness and comparative information to previous boxing studies. Further discussion on methodology is provided in Chapter 3.

2.5.4 Time Loss

Hand-wrist injuries incurred in GB Boxing athletes during 2005-2012 accounted for a total of 7712 days lost (79 days lost per boxer per hand-wrist injury) affecting training availability (Loosemore et al., 2017). In this study, the total number of days affecting training availability from CMC injuries (n=2009) exceeded the total for other types of injuries. During a more recent but shorter period, 2016-2021, hand-wrist injuries resulted in a total of 8924 days lost (121 days lost per boxer per hand-wrist injury) affecting training availability, with more days affecting training availability from injuries incurred in training (n=4966) than in competition (n=3958) (Saunders, 2022).

Specifically, CMC injuries account for a total of 1935 days lost (28 days lost per boxer per injury) affecting training availability (Saunders, 2022). A lower incidence rate but increased days affecting training availability from CMC injuries incurred in competition (n=8, n=1141 respectively) than in training (n=13, n=794 respectively) (Saunders, 2022). It therefore appears that for CMC injuries, more days affect training availability when incurred in competition (n=142/injury) rather than in training (n=61/injury).

When calculating injuries per rate of exposure, specifically for CMC injuries, a higher rate of injuries was observed in competition (n=110 /1000 hours of exposure) than in training (n=13 /1000 hours of exposure) (Saunders, 2022). Considering more limitations in bandaging materials and techniques are present in competition than in training (International Boxing Association, 2023), the role of bandaging, as a factor towards both injury severity and rate of exposure, needs to be considered. The role of bandaging will be discussed further in Section 2.7 and Chapter 6.

2.5.5 Gender Considerations

Women's boxing was introduced to the OG in London 2012, with three weight categories. This participation has continued at subsequent OG. Women's weight categories have increased, with a reciprocal reduction for their male counterparts. There were 10 men and 3 women categories at the London 2012 and Rio 2016 OG, 8 men and 5 women categories in Tokyo 2020 OG, and 7 men and 6 women categories scheduled for the Paris 2024 OG.

Despite increased participation of women in Olympic boxing in the last decade, no studies have investigated gender differences in boxing. From a retrospective data analysis performed at GB Boxing between October 2016 and September 2021, it was evident that males sustained more upper limb injuries (n=208, 73.5%) than females (n=75, 21.2%) (Saunders, 2022). However, this prevalence of gender difference could have been due to the study having more males (n=44) than females (n=24). Upper limb injury prevalence rates per boxer were however higher in males (n=5) than females (n=3). Similarly, hand-wrist injuries in male boxers represented both a higher total prevalence (n=136) and injury per boxer (n=3) than the total prevalence (n=45) and injury per boxer (n=2) in female boxers (Saunders, 2022).

Higher injury rates in male boxers cannot be attributed to differences between bout structure. All genders adopt a similar number of minutes per round, rounds per bout, and bouts per competition. Other factors should therefore be considered, like shot velocities. Kimm and Thiel (2015) considered differences between mean and maximal shot velocities of 10 males and 6 females when throwing 20 Jab and 20 cross shots in the air, with no contact onto a target. The mean (and standard deviation) velocity for men was 8.1±1.4 and 7.7±1.5 m/s respectively for Jab and Cross shots, and for females was 6.6±1.6 and 5.7±1.5 m/s. The authors observed no significant difference between the velocities of the different hands in both groups. Further, the authors concluded that the relationship between maximal hand velocity and years of experience indicated that the latter contributed to over half of the former irrespective of gender, age, and reach. Considering most male boxers in Britain have more overall experience (training and competition) than their female counterparts, the former could likely produce more velocity when throwing shots. Whether more hand velocity can result in more hand-wrist injuries is hard to quantify, as this has not been studied.

In a study using *in-vivo* markerless bone registration technique applied to computerised tomography (CT) scans of 26 male and 28 female wrists, kinematics was quantified with variations described as occurring due to bone size rather than gender differences (Rainbow et al., 2008). Gender differences should be considered especially due to physiological differences such as decreased muscle and bone mass percentage, these being risk factors for injuries (Blair, 2007). Further, females generally have increased flexibility of the muscle-tendon unit reducing injury risk and benefitting performance (Witvrouw et al., 2004).

Similar to amateur style boxing, it appears that males have a higher rate of injuries than females in professional style boxing (Bledsoe, Li and Levy, 2005). Data from all professional boxing matches over a 3-year period (n= 524 matches) showed significantly more hand injuries in males (n=33) than females (n=0) (Bledsoe et al., 2005). There are similarities between male and female regulations in professional boxing with glove weights and number of rounds being equal, however, females typically have shorter round duration (2 mins) than males (3 mins). Although not considered by the authors of this study, a reduced round duration for females, compared to men, would reduce the rate of exposure. This difference in round duration is a plausible factor in explaining the incidence rates observed in this study. In Olympic boxing, the number of rounds for female boxers is currently similar to the men, the only difference being that women must wear headguards (International Boxing Association, 2023). Wearing headguards could possibly provide some cushioning, reducing kinetic forces acting on the hand-wrist on impact to the head, which could account for fewer injuries in women than men in the amateurs (Saunders, 2022). As headguards are worn by both genders in training, but not by men in competition, it could likely provide another factor why males incur higher hand-wrist injury rates than female boxers.

Although gender differences were not studied in this programme of research, this factor was considered when approaching the individual studies conducted and presented in Chapters 5 and 6. With a higher incidence of hand injuries, specifically CMC injuries in male than in female boxers, focusing on the males was felt appropriate for this programme of research.

2.5.6 Mechanism of Injury

Hand injuries in boxing, specifically at the CMC region, occur directly due to participation in the sport, unlike other injuries which can occur indirectly or not related to the sport (International Olympic Committee Injury and Illness Epidemiology Consensus Group, 2020). The mechanism of injury is always reported as direct contact with another athlete, typically on a bony (hard) surface like the top of the opponent’s head. When a shot is thrown correctly, the index and middle finger knuckles display the largest proportion of impact forces (Loosemore et al., 2015b), explaining why CMC injuries at the index and middle finger are more common than at the other fingers (Loosemore et al., 2017; 2015a; Matharu et al., 2022a; Melone, Polatsch and Beldner, 2009).

When punching (i.e., landing a boxing shot on a target), the fingers are curled into the palm to support the thenar and hypothenar eminences, with force transmitted from the metacarpophalangeal (MCP) through the CMC joints, up the kinetic chain of the upper extremity (Eschweiler et al., 2022; Loosemore et al, 2015b). As little movement occurs at the index and middle finger CMC joints (Morgan and Carrier, 2013), they are loaded when a shot is thrown correctly. Loading of the CMC joints is supported through investigations of proportional distribution of impact forces, using pressure films placed over the knuckles (Loosemore et al., 2015b). The middle and ring finger knuckle display the largest and lowest proportion of impact forces, respectively (Loosemore et al., 2015b). It is likely that punching forces are absorbed mainly upon the knuckles, and therefore responsible for the serious hand injuries that have been reported in several case studies (Hame and Melone, 2000). This has also led to the term boxer’s knuckle becoming widely used (Gladden, 1957). Index and middle finger

CMC injuries are however more common than those at the other fingers (Matharu et al., 2022b; Loosemore et al., 2017; Melone et al., 2009; Nazarian et al., 2014). The distribution of impact forces along the hand and into the wrist during punching are perhaps important for injury risk.

Higher force transmission towards the radial side of the wrist is supported by the literature, as observed when a load is applied to the hand using a rigid body spring model (Schuind et al., 1995). In this study it was observed that 90% of the total radio-ulno-carpal force was transmitted through the radius with 61% through the radio-scaphoid joint and 39% through the radio-lunate joint. Around 10% of the remaining force was dissipated on the ulnar side of the wrist through the triangular fibrocartilage complex (83% from the lunate and 17% from the triquetrum). Further, the distribution of the forces (Figure 2.7) in the MiC joint was 30% through the STT joint (32% through the scapho-capitate joint, 27% through the luno-capitate joint, and 11% through the triquetral-hamate joint). Each CMC joint transmitted on average 26.2 N (10.1-45.7 N), with higher forces on the radial than ulnar CMC joints.

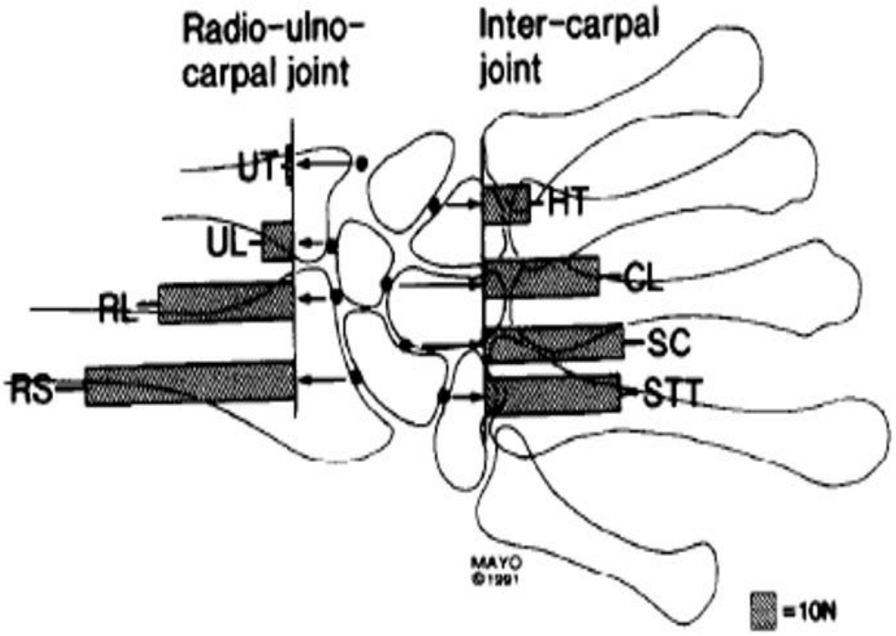
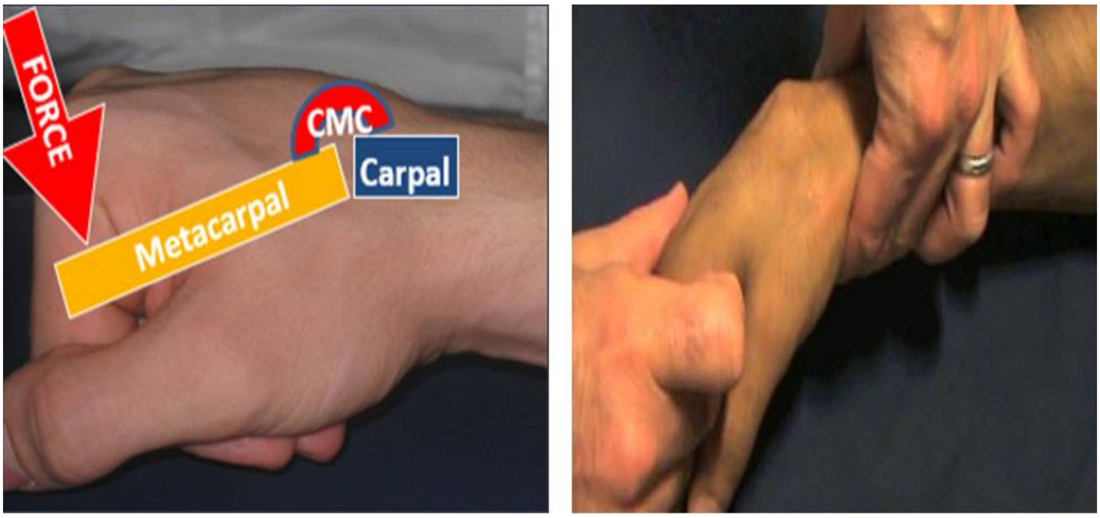


Figure 2.7: Resultant forces in the radio-ulno-carpal and intercarpal joints**.** *Figure source from Schuind et al. (1995).*

Forced FLEX (Figure 2.8) is a primary mechanism leading to injuries at the hand-wrist complex (Noble, 1987), as observed at elite amateur boxing level (Matharu et al., 2022a). As a boxer fatigues, the wrist tends to collapse under load into FLEX, which produces strain across the dorsum of the CMC joint (Morgan and Carrier, 2013). Fatigue in a joint has been described to reduce its stability (Panjabi, 1992), as discussed in Section 2.4. Strain at the CMC joints will eccentrically load the ECRL and ECRB muscles, with both muscles observed to have a significant role in increasing wrist stability (Holmes, Tat and Kier, 2015). ECRL and ECRB attach at the base of the index and middle MC bones, implying their role in stabilising their respective CMC joints, beyond the wrist joint. Excessive loading of these muscles can however lead to injuries. These injuries can be clinically observed through concomitant avulsion of either or both ECRL and ECRB tendons attachments (Mundell, Miladore and Ruiter, 2014; Najefi, et al., 2016; Nazarian et al., 2014).



a) b)

Figure 2.8: Injury mechanism and assessment of CMC joints with a) illustration of dorsal ligaments and ‘force’ on impact flexing the CMC joint and b) Carpal Seesaw (aka Piano Key) test showing laxity at both index and middle finger CMC joints in a boxer.

ECRL and ECRB muscles are typically described to perform combined EXT and RD of the wrist (Tanrıkulu et al., 2015), the opposing action of ulnoflexion motion. Both these combined actions, as mentioned, are the DTM mechanism typically occurring at the wrist in various activities. As forced FLEX at the wrist appears to be the likely mechanism of injury towards CMC joints, and considering that FLEX couples with UD, ulnoflexion could potentially occur on impact in boxing.

2.5.7 Clinical Presentation and Management

The anatomical structures most affected in hand-wrist injuries are ligaments and joints (Saunders, 2022). These anatomical structures are typically injured by sudden activity and trauma (Li and Niu, 2020), corresponding to the typical mechanism of hand-wrist injuries in boxing (Section 2.5.6). Hand-wrist injuries in boxing typically occur when direct sudden contact (i.e., single episode trauma) occurs between the glove and the opponent (Saunders, 2022; Loosemore et al., 2017). This single episode injury mechanism explains why the hand-wrist region, specifically the CMC joints, typically present with higher severity (intensity of symptoms and time loss from training) than other injuries incurring a repetitive mechanism (Matharu et al., 2022a; Saunders, 2022; Loosemore et al., 2017).

Due to higher severity of CMC injuries, specifically at the index and middle finger as compared to other injuries (Saunders, 2022; Loosemore et al., 2017; 2015a), it is unsurprising that these are the most operated anatomical sites at the hand in boxing (Matharu et al., 2022a). These CMC injuries usually present with pain and laxity (i.e., instability) (Matharu et al., 2022a). A useful clinical test to localise pain and joint laxity, Carpal Seesaw Test (Figure 2.7b), involves stressing the CMC joint into FLEX (Matharu et al., 2022a).

Functionally when there is a hand-wrist injury, there is an inability to perform a full fist on the injured side with the same force as the uninjured side (Gatt et al., 2018). When using a handgrip dynamometer as an objective measure (Figure 2.9), a mean percentage of 38.1% (7.7%-81.2%) has been observed when compared with a baseline of 5.5% (1.0%-14.7%), indicating a higher percentage difference for CMC injuries than other regions (Gatt et al., 2018). This inability to make a fist, when injured, leads to difficulty in activities of daily living which involve gripping. It also reduces the ability to make a fist during punching, important for hand-wrist stability (Holmes, Tat and Keir, 2015; Salva-Coll et al., 2011), likely causing further trauma to injured areas.

Figure 2.9: Hand grip dynamometer test assessing peak force. A test typically used as functional assessment for CMC injuries in boxing.

Diagnosis of hand-wrist injuries, specifically at the CMC joint, can be made using history and joint instability demonstrated at clinical examination (Matharu et al., 2022a). An ultrasound scan allows for the assessment of dynamic instability with dorsal CMC joint opening, whereas an MRI visualises the dorsal ligament and bone oedema in the unstable joints. Often marked deficiency in the CMC ligamentous capsule has been observed (Matharu et al., 2022a). A CT scan is typically reserved for cases in which clinical instability was equivocal (Matharu et al., 2022a).

CMC fusion with fixation into EXT using various methods, is the technique that has been most successful as defined through radiographic fusion, return to boxing, and consideration of potential complications (Matharu et al., 2022a). Attempting to repair the dorsal ligament rather than fuse the joint can lead to failure (Matharu et al., 2022a) This repair technique has been unsuccessfully trialled on a boxer, indicating that once the dorsal ligament fails it is not possible to achieve the same stability in a sport like boxing (Matharu et al., 2022a). Of note, the boxer was amateur and competed wearing cotton bandages only.

Return to initial hitting activities (i.e., impact) is typically allowed around 8 weeks post-surgery, after an encouraging radiograph. Using a graduated loading approach, increasing hitting activities is possible at 12 to 16 weeks, if no adverse reaction or pain develops (Matharu et al., 2022a). The use of a removable brace (Figure 2.10), in the initial stage of return to loading, has been observed anecdotally to reduce pain and improve training availability. This brace, or wrist protector, is aimed at limiting hand-wrist motion and therefore reducing forces acting at the CMC. Similar protectors, to those used in snowboarding, have been observed to reduce motion and kinetic forces at the wrist during impact activities (Leslie et al., 2023; Adams et al., 2021).

This brace is thereafter removed, whilst ensuring adequate rigid tape is applied to limit wrist motion. Less motion and more passive support are likely occurring with a brace compared to rigid tape, potentially reducing the role of muscles and other anatomical structures to provide active stability. Applying rigid tape to a bandage likely provides a somewhat similar effect on the requirement of muscle function on active stability, when compared to using bandage only. The role of bandaging will be discussed in more detail in Section 2.6 and Chapter 6.

Figure 2.10: Hand-Wrist off-the-shelf brace used for various medical applications.

2.5.8 Whole Body Kinematics

The kinematics of boxing involve a complex interplay of footwork, shots, and head movement, all aimed at achieving strategic advantages and ultimately landing effective shots on the opponent while avoiding being hit (Beattie and Ruddock, 2022; Chen et al., 2021; Lenetsky et al., 2020). Shots are typically divided into two categories: Jabs and power shots. Jabs are quick, straight shots thrown with the lead hand, while power shots are more powerful, circular shots thrown with either lead or rear arm.

A key fundamental when throwing a shot is stance. Stance is the basic position from which all movements and shots are initiated. A conventional stance involves standing with the feet shoulder width apart, the knees slightly bent, and the body positioned slightly to the side ensuring a smaller target area is shown to the opponent. The hands are conventionally held up, with the lead hand (the one closest to the opponent) held slightly higher to protect the face region. Of note some boxers prefer choosing a style where the arms are held down. This style is popular amongst counterpunching boxers who aim to draw in more attacking style boxers by having a ‘lowered’ guard. A boxer can adopt either an Orthodox (places their left foot further in front of the right one, thus having their left arm closer to the opponent) or Southpaw (places their right foot further in front of the left one, thus having their right arm closer to the opponent) stance. Orthodox boxers (75%) are the general right-handed position and are more common than Southpaw boxers (25%), being a natural left-hander’s position (Sorokowski, Sabiniewicz and Wacewicz, 2014). As Southpaw boxers are uncommon, they are more challenging to recruit for studies. This formed the rationale for selecting Orthodox boxers in the studies described in Chapters 4 to 6.

In boxing there are six shot types, divided between the lead and rear arm. The lead arm comprises; Jab, lead Hook, and lead Uppercut. The back arm comprises; Cross, rear Hook, and rear Uppercut. Jab and Cross shots are both straight arm shots, whereas all other shots are described as bent arm shots (Lenetsky et al., 2020). While injuries at the hand can occur with all shot types in boxing, straight arm shots appear to contribute more to CMC joint injuries than bent arm shots. Further, CMC injuries do not typically occur with uppercut shots. This is difference in injuries observed anecdotally between straight and bent arm shots, is possibly explained through kinematics analysis of shots and the system of levers. Straight arm shots have been shown to exhibit a proximal-to-distal sequence for the shoulder and elbow joints, respectively, with the shoulder reaching peak angular joint velocity before the elbow (Stanley et al., 2018). Meanwhile, bent arm shots do not exhibit upper limb proximal-to-distal sequencing as peak angular elbow joint velocity occurs before that of the shoulder joint (Stanley et al., 2018). This difference between shot types, in proximal-to-distal sequencing, indicates that changes in muscular length between muscles crossing the wrist and elbow joint occur more with straight than bent arm shots.

Using standard terminology of levers (Bejnke, 2012), the hand would be the lever, the wrist tendons tension the effort, the wrist joint the fulcrum, and the forces on impact the resistance. With a straight arm the wrist tendons, which originate at the lateral epicondyle and are therefore anatomically located proximal to the elbow joint, are under higher tension than with a bent arm due to changes in muscle-length during the shot. This higher tension in muscle tendons, occurring between straight and bent arm positions, indicates increased muscular force required to maintain a stable wrist (i.e., active stability). The hand-wrist region is also further from the boxer’s centre of gravity, with a straight than bent arm shot, likely indicating more proximal dynamic stability at the shoulder when a shot lands on their opponent. Further, straight arm shots have a shorter duration than bent arm shots (Stanley et al., 2018), giving less time for the neuromuscular system of the body to create active muscular control or stiffness, distally at the hand-wrist region. Therefore, it is expected that straight arm shots might exhibit more wrist angular excursion on impact than bent arm shots, due to the increased requirement of dynamic control on shot impact, explaining why more injuries are anecdotally observed in straight than bent arm shots.

In boxing, upper limb kinematics play a crucial role in delivering powerful and accurate shots while minimising injury risk. The execution of a shot is dependent upon a proximal-to-distal sequencing pattern initiated by the lower limbs that travels distally through the pelvis, trunk, and arm before peaking at the fist, causing its acceleration towards the target (Cheraghi et al, 2014). Typically, the sequence of motion from the lower limb to trunk to upper limb (proximal-to-distal sequence), when a boxer throws a shot, is characterised by a consecutive sequence of motion (CSM). There is however an emerging theory towards simultaneous sequence of motion (SSM) (Newell and Irwin, 2021).

In a study using four experienced martial artists, differences between CSM and SSM were assessed (Fuchs, Lindinger and Schwameder, 2018). It was observed that CSM shots provided higher fist velocity with lower stance stability as compared to SSM. The authors therefore suggested CSM was more effective for generating power shots and SSM for bridging (especially close) distance in a short time. If stance stability is valued highly, SSM could improve stance stability especially if short execution time is prioritised over high physical impact.

Fuchs, Lindinger and Schwameder (2018) considered that depending on the individual fighting style, environmental setting and situational requirements, every athlete could decide which execution is more suitable. Considering boxers throw different shot types over short periods of time, there could be potential variations of CSM and SSM occurring during a competitive event. Since the kinematics in the upper limb appear to alter between CSM and SSM (Fuchs, Lindinger and Schwameder, 2018), there could be implications for hand-wrist injuries.

Stanley et al (2018) observed that this concept of SSM and CSM is already present, in the upper limb, between both straight and bent arm shot types. Straight arm shots exhibit CSM, whilst bent arm shots exhibit SSM, in the upper limb. This finding conflicts with the suggestion by Fuchs, Lindinger and Schwameder, (2018) that CSM is more effective for generating power shots and SSM for bridging the distance in a short time. Straight arm shots occur in a shorter time than bent arm shots, with the latter generating more power due to a longer path (Stanley et al., 2018). Whether changes from CSM to SSM in the rest of the kinetic chain (lower limb and trunk) could influence wrist motion, and therefore injuries are debatable. Differences in shot types, however, could likely affect wrist kinematics due to the system of levers discussed earlier in this section. The difference between shot types is discussed in more detail in Chapter 5.

The four main criteria to win a competitive bout in amateur boxing, as defined by the International Boxing Association (2023), are; a) quality shots landed on the opponent, b) dominance; tactical and technical, c) competitiveness; attitude in the ring, and d) infringement of rules. To achieve ‘quality,’ shots must land with sufficient force on impact to capture the attention of the judges scoring the bout. Impact has been defined as a force resulting from the collision of two or more bodies over a relatively short time (Nigg, 1985). The effect of the impact depends on the amount of force applied at the collision moment, which in turn depends on the relative velocity of the bodies to one another (Stronge, 2000).

Shot velocities have been suggested to be dependent upon the length of the acceleration path to the target (Piorkowski, Lees and Barton, 2011; Whiting, Gregor, and Finerman, 1988). Hook (bent arm) shots have been observed to possess longer acceleration pathways, which would explain greater pre-impact fist velocities, compared to Jab (straight arm) (Piorkowski, Lees and Barton, 2011; Whiting, Gregor, and Finerman, 1988). As mentioned, bent arm shots fail to exhibit a proximal-to-distal sequence due to the fixed elbow position associated with them. Indeed, during straight arm shots, the elbow joint rapidly extends after the arm has already started accelerating towards the target via angular velocities generated at the shoulder joint (Cheraghi et al., 2014; Jessop and Pain, 2016). However, during Hook shots, the elbow is flexed, fixed to an approximate right angle, whilst the shoulder exhibits a rapid combination of abduction followed by FLEX, protraction, and adduction from start of the shot to target contact (Piorkowski, Lees and Barton, 2011; Whiting, Gregor, and Finerman, 1988). The difference in motion contribution of shoulder, as compared to elbow, might explain why peak angular velocities at the shoulder joint are markedly higher than those at the elbow across Hooks as compared to Jabs (Dinu and Louis, 2020; Piorkowski, Lees and Barton, 2011; Whiting, Gregor, and Finerman, 1988).

Higher peak shot velocities of Hook over Jab shots corroborate the findings of another study where the lead and rear Hook was observed to generate greater fist velocities than the Jab and rear-hand Cross, respectively (Piorkowski, Lees and Barton, 2011). Higher shot velocities of Hook over Jab shots can be explained by the greater ROM available at the shoulder joint in comparison to the elbow (Loturco et al., 2016; Piorkowski, Lees and Barton, 2011; Whiting, Gregor, and Finerman, 1988).

Dinu and Louis (2020) showed the percentage contribution of motion occurring during different shot types varies. In this study, straight arm shots had the highest contribution coming from the elbow joint as compared to the shoulder, trunk, and pelvis motions. Bent arm shots however showed the highest contribution coming from the shoulder as compared to elbow, trunk, and pelvis motions. Bent arm shot velocities (10.2-11.2 m/s) were observed to be greater than straight arm shots (8.1 m/s) (Dinu and Louis, 2020).

The rear Hook has been shown to have the greatest peak resultant fist velocity of all shot types (Piorkowski, Lees and Barton, 2011). Conversely a more recent study observed the lead Hook, rather than the rear one, to have the greatest peak resultant fist velocity (Stanley, et al., 2018). This conflict is likely a consequence of the computer-based scoring system used in 2011. That is, a high frequency of Jab punches alongside a likely more effective rear hand punch, particularly the rear Hook, was favoured for points scoring. Accordingly, the boxers assessed in Piorkowski, Lees and Barton (2011) probably possessed greater technical competency for the rear Hook than those in the Stanley et al (2018) study. Under the scoring system present at the time of the Stanley et al (2018) study, boxers were expected to execute lead Hook punches more frequently, likely possessing an improved aptitude for this technique. Based on the results from both studies it appears that either Hook punches, lead or rear, will provide the greatest peak resultant velocity when compared to Jab or Uppercut shots. Based on the scoring rules present at the time of the proposed studies in this programme of research, and the results from Stanley et al (2018), it was felt that choosing the lead Hook would be appropriate as one of the shots being selected.

The shortest delivery times across all shot types were observed in the straight shots owing to their linear trajectory from the initial position and travelling the least distance to the target (Stanley et al., 2018; Piorkowski, Lees and Barton, 2011). The Jab has the shortest delivery time, which would explain why it is the most frequently executed shot within competition (Kapo et al., 2008; Thomson and Lamb, 2016). Choosing the Jab shot was therefore considered an important choice as one of the shots selected for assessment in this programme of research.

Experience can also influence upper limb kinematics. Mean (and standard deviation) maximal shot velocities, for all shot types, have been recorded at 9.8 ± 2.3 and 8.1 ± 1.2 m/s for elite and less experienced boxers respectively (Dinu and Louis, 2020). These metrics appear to agree with other studies in boxing, together with other combat sports like karate and kung-fu (Lenetsky, Harris, and Brughelli, 2013; Neto, Magini and Saba, 2007; Wilk, McNair and Feld, 1983). Hand peak non-contact maximal velocities, as high as 9 m/s, were also observed depending on the type of punch: Jab, Cross, lead Hook and reverse Hook (Kimm and Thiel, 2015). This agrees with another study where single maximal shot contact speeds of 8.16 m/s were observed (Walilko, Viano and Bir, 2005). Conversely, shot velocities as low as 4.18-5.14m/s have been recorded (Bergün et al., 2017). These shot velocities (Bergün et al., 2017) were lower when compared to other studies (Dinu and Louis, 2020; Kimm and Thiel, 2015; Walilko et al., 2005). The authors commented this could be due to lesser experience of this cohort, as compared to other studies (Bergün et al., 2017).

Shoulder contribution has been observed to be higher in less experienced boxers for both straight and bent arm shots (Dinu and Louis, 2020). The trunk segment contribution has also been observed to be higher for straight arm shots in less experienced boxers (Dinu and Louis, 2020). Similarly, the pelvis contribution also showed contribution differences with greater motion occurring in the linear plane (i.e., antero-postero direction), for the Hook only, in less experienced boxers (Dinu and Louis, 2020). Whether increased motion at the shoulder, trunk and pelvis can contribute indirectly towards more hand-wrist injuries is hard to corroborate. Less experienced boxers are typically anecdotally observed to have more injuries. Most boxers have also been observed anecdotally to improve their longitudinal rates of injuries, especially in the upper limb region, as their experience increases. Considering that there are known proximal-to-distal segmental contributions, especially in straight arm shots (Stanley et al., 2018), changes in wrist motion could likely be occurring in less as compared to more experienced boxers.

To date no studies have been conducted on wrist kinematics in boxing. Experience was not an initial objective in this programme of research. However, this factor was considered when comparing the results from two studies (Gatt, Allen and Wheat; 2023; 2021), conducted as part of this programme of research. More information on experience and wrist kinematics is provided in Chapters 6 and 7.

2.5.9 Kinetics in Boxing

There are three main contributors of punching force for a shot; a) the drive off the lower limbs, b) the rotation of the trunk, and c) the strength and stability of the upper limb (Lenetsky, Harris and Brughelli, 2013). Punching force is therefore not just a representation of how strong a boxer is but rather a coordination of the entire body to maximise the force, especially when landing shots. When considering the whole body, a general propulsion forward was found towards the target in straight arm shots (Stanley et al, 2018). In Hook shots, the propulsion was more lateral whilst still included some forward movement toward the target (Stanley et al, 2018). This difference in propulsion direction can be explained by straight arm shots being initiated further away from the target than bent arm shots (Lenetsky, Harris and Brughelli, 2013). In straight arm shots, a boxer is required to reduce the distance between themselves and the target, which is lessened in bent arm shots (Lenetsky, Harris and Brughelli, 2013). This forward motion, by the whole body, could be a potential factor for incurring more injuries in the hand-wrist with straight than bent arm shots, especially if errors are made when judging the distance with a moving opponent.

Both straight and bent arm shots appear to counteract the propulsion towards the target using the contralateral leg to the punching arm (Stanley et al., 2018). The resulting forces, however, do not appear to create equilibrium as whole-body forward motion is observed in both shot types (Stanley et al., 2018). It therefore appears that the lower limb on the punching arm needs the ability to generate propulsion force, whereas the contralateral side necessitates the ability to generate a blocking force. This blocking action is likely important to increase hip rotation velocities converting linear to angular momentum (Turner, Baker and Miller, 2011). This conversion in momentum (i.e., impulse) is a key component in throwing effective shots, as this impulse is then transmitted up the kinetic chain to the rest of the trunk, shoulder, fist and then target (Turner, Baker and Miller, 2011). Muscular strength or timing deficits could therefore affect the correct execution of a shot, which in turn could influence various upper limb injuries.

In the wider boxing community, it is generally considered that strengthening the upper limb region can improve the force of shots. Although there may be a contribution from the upper limb it appears that the lower body likely provides a higher contribution to the force of a shot. The relationship between impact force and both upper and lower body force was assessed in a highly trained group of 28 male amateur boxers (Dunn et al., 2022). In this study, shot performance was assessed using a 3-minute maximal effort shot test using both straight and bent arm shots, for both lead and rear shots. Peak shot force and force-time variables were assessed which included impulse and rate of force development (RFD). Force, power, and RFD of the upper and lower body were assessed with countermovement bench throw, isometric bench push, countermovement jump (CMJ), and isometric midthigh pull (IMTP) tests. Significant relationships were observed between peak force and forces measured in the lower limb using the CMJ and IMTP tests (Dunn et al., 2022). Further peak shot force was moderately and significantly correlated to body mass. However, no meaningful relationships between shot performance characteristics and upper-body strength or power parameters were identified. Although upper-body strength and power were expected to be important in boxing, the authors observed that these metrics did not differentiate between boxers who threw shots with higher or lower peak force, nor were they correlated to peak shot force (Dunn et al., 2022). The authors further proposed that training that improves lower-body strength, without increasing total body mass (maintaining weight category,) may positively influence shot performance in highly trained amateur boxers.

It is important to emphasise that in complex movements, such as boxing shots, the impact forces are the resultant of the sum of the forces applied simultaneously by the upper and lower limbs. When boxers throw shots at high velocities, the ability to transfer the momentum from the legs to the arms is determinant in achieving high impact forces (Lenetsky, Harris, and Brughelli, 2013; Turner, Baker, and Miller, 2011). This is consistent with the results of a study where shot force and strength characteristics were assessed in fifteen elite amateur boxers from the Brazilian National Team (Loturco et al., 2016). Loturco et al., (2016) observed that both upper and lower body measures of strength correlated with peak force output for both lead straight and bent arm shots. Of note though, only maximal isometric strength of the squat in the lower limbs presented significant high correlations with peak force for shots (Loturco et al., 2016). Dunn et al., (2022) however observed that upper body measures of strength did not correlate with peak force. These results reinforce the importance of the lower limbs in generating force during shots, however not completely disregarding the role of the upper limb in peak force of shots.

In a later study, the effect of resistance-training on peak shot force on a group of twelve elite amateur boxers from the Brazilian National Olympic Team was assessed (Loturco et al., 2018). In this study, bench press (BP) and jump squat (JS) exercises were used to identify optimal power loads over a 7-week training period. Power outputs increased for both BP (+8%) and JS (+7%). Whether this improvement in both upper and lower limb metrics had a pragmatic effect on peak shot force is unclear as this was not assessed. Further, even if this were assessed, it would have been hard to discriminate which body region improvement contributed as both upper and lower regions were trained simultaneously. Future studies looking at direct relationships of training with peak shot force should therefore be considered.

The stance of a boxer (i.e., Orthodox vs Southpaw), and therefore differences between the lead and rear arms, should be considered towards forces generated on impact. Chadli, Ababou, and Ababou, (2014) observed shot forces were larger for the rear than the lead hand. These differences in shot forces produced by the rear and lead hands are likely related to the force generated by the lower limbs (Lenetsky, Harris, and Brughelli, 2013; Smith et al., 2000). The boxers initiate the shot through the leg determined by lower body joints kinematics (Cheraghi et al., 2014). Considering lower limb force highly contributes to maximal shot force (Lenetsky, Harris, and Brughelli, 2013; Turner, Baker and Miller, 2011), boxer stance positions could likely change this force.

Significantly lower impact forces for Southpaw (1616.96±434.92N) than Orthodox (1987.42±341.95N) stance were observed when throwing shots with only the right side for nine elite amateur boxers (Bergün et al., 2017). The authors concluded that this significant difference was due to the lower shot velocity. This suggestion is plausible, because the further the hand travels, the more time there is to accelerate even though a boxer’s fist may take longer to reach its target. Of note, the boxers in this study were likely orthodox boxers, although not stated, suggesting another reason for the significant difference observed was due to technique (i.e., an Orthodox boxer would not switch to a Southpaw stance).

Peak fist velocities on impact have also been shown to be higher in the rear arm (6.97 m/s) than the lead arm (5.85 m/s), in straight arm shots (Stanley et al., 2018). It has been described that each boxer maintains a preferred stance in both training and competition, which is usually determined by keeping the stronger arm in the back

(Sorokowski, Sabiniewicz and Wacewicz, 2014). The influence of stance, and therefore the individual lower legs in throwing shots, is therefore important as also shown elsewhere (Stanley et al., 2018). In this study, the total rear leg net propulsive impulse was higher when delivering a cross (66.6± 38.4 Ns/kg) than when delivering a Jab (29.2 ± 20.1 Ns/kg) (Stanley et al., 2018). Of interest during a recent 5-year period (2016-2021) it was observed that in the GB Boxing programme, boxers that adopt an Orthodox stance sustained the most upper limb injuries (n=189, 66.7%), likely due to it being the predominant boxing stance used by 46 of 68 boxers (71%) (Saunders, 2022). Boxers with a Southpaw style stance had 94 (33.2%) upper limb injuries across 22 of 68 boxers (Saunders, 2022). Although injuries were higher in Orthodox than Southpaw stance boxers, a slightly higher injury rate per boxer was observed in Southpaw stance (n=4.27) than in Orthodox stance (n=4.10) boxers (Saunders, 2022). Hand-wrist injuries were the most frequently sustained region, with Orthodox (n=115) more than southpaw (n=66) (Saunders, 2022). The rate of injuries per boxer located at the hand and wrist was observed to be similar between Southpaw (n=3) and Orthodox stance (n= 2.5) (Saunders, 2022). It therefore appears that stance is not a factor linked to injury prevalence.

Considering punch forces are a result of whole-body contributions, it is unsurprising to find that studies report different peak shot forces (Table 2.4). Pierce et al (2007) obtained forces collected using a proprietary glove embedded system during six professional matches across five different weight classes (Pierce et al., 2007). Peak forces (1205 N) obtained in this study (Pierce et., 2007; Table 2.4) were lower than the forces (1990 to 4741 N) obtained from other studies performed in laboratory settings (Table 2.4). Most of the studies outlined in Table 2.4 agree that the Cross shot

Table 2.4: Punching force measured in various boxing studies. *Recreated and amended from Lenetsky et al. (2013).*

Study	Subjects (Boxers)	Measuring Equipment	Punches Tested	Punch Peak Forces (N)
(Atha et al., 1985)	Professional (n = 1)	Padded pendulum equipped with piezoelectric force transducer	Unidentified	4096
(Dinu and Louis, 2020)	Elite (n = 15) and Junior (n=7)	An instrumented suit composed of 17 inertial measurement units (IMU)	Elite Rear Cross Elite Rear Hook Elite Rear Uppercut Junior Rear Cross Junior Rear Hook Junior Rear Uppercut	3158 ± 1,467 2999 ± 1,818 3242 ± 1,767 1021 ± 449 544 ± 235 700 ± 287
Dyson et al., 2008)	Amateur (n = 6)	Boxing dynamometer mannikin	Lead Straight Rear Straight	2082 ± 62
(Pierce et al., 2007)	Professional (n=12)	Best shot force sensor impeded in boxing gloves	Unidentified	1205
(Smith et al., 2000)	Elite (n = 7), Intermediate (n = 8), and Novice (n = 8)	Wall-mounted force plate (4 triaxial piezoelectric force transducers) with a boxing manikin cover	Elite rear hand mean force Elite front hand Intermediate rear hand Intermediate front hand Novice rear hand Novice front hand	4800 ± 227 2847 ± 225 3722 ± 133 2283 ± 126 2381 ± 116 1604 ± 97
(Walilko et al., 2005)	Amateur (*n* = 7)	Dummy equipped with a 6-axis load cell in the neck and a Tekscan pressure sensor in the face. Endevco accelerometers on the boxer's hands	Straight Punch	1990-4741

will produce a larger force than the Jab shot, and that a lead Hook shot will produce more force than a Cross. These differences in forces between shot types, should be considered when discussing potential kinematic variances occurring at the wrist on impact.

Similar to kinematic differences discussed before, experience appears to have influence on peak force production of a shot. In a study comparing elite and junior athletes, wearing an instrumented suit composed of 17 inertial measurement units (IMU), peak shot forces (Table 2.4) were greater in the elite group (Dinu and Louis, 2020). In another study, a boxing dynamometer was developed by combining a tri-axial force measurement system and a boxing mannequin (Smith et al., 2000). The dynamometer was used to compare the punching force of 7 elite, 8 intermediate and 8 novice boxers during straight shots. Mean punching forces (Table 2.4) were significantly greater in the more experienced boxers. The effect of experience on injury rates has been observed in various sports (Alekseyev et al., 2020; Zetaruk, et al., 2005; 2000). In boxing, more injuries have been observed in amateur style boxers as compared to professional boxers in competition (Zazrynm, Cameron and McCrory, 2006). Amateur boxers typically progress to the professional style. It is therefore considered that professional boxers are more experienced than amateur boxers. Within the amateur style, more injuries are typically observed at the hand-wrist region with boxers having lesser experience as part of the GB Squad. Therefore, as both whole body kinematics and kinetics appear to be influenced by experience in boxing, this topic requires some consideration. Further discussion on experience is provided in Chapters 6 and 7.

2.5.10 Local Hand-Wrist Strength

The wrist plays a crucial role in maintaining stability on contact, ensuring the force generated from the proximal-to-distal sequencing pattern, initiated by the lower limbs is transferred to the opponent (Lenetsky et al., 2020; Newell and Irwin, 2021). During a shot, the arm starts from the guarded position which maintains a bent elbow and forearm position in a relative neutral or supinated position (Lenetsky et al., 2020). During the execution phase of a straight arm shot, the torso rotates followed by the shoulder moving towards the target (Lenetsky et al., 2020). With continued rotation of the torso, the elbow extends together with forearm pronation (fist turning palm down), this rotation likely generating additional force to the shot (Lenetsky et al., 2020). Conversely to straight arm shots, a bent arm shot, like the Hook, will use less contribution at the elbow and forearm (Lenetsky et al., 2020; Dinu and Louis, 2020).

In addition to the individual movements of the shoulder, elbow, and forearm, effective boxing requires precise coordination between these joints (Fuchs, Lindinger and Schwameder, 2018; Lenetsky et al., 2020; Newell and Irwin, 2021), as well as the positioning and control of the hand-wrist region. A boxer must be able to quickly and accurately adjust the position of their upper limbs to deliver a punch while maintaining balance and avoiding incoming shots (Lenetsky et al., 2020; Newell and Irwin, 2021). Boxers tend to have a relatively loose fist, and as in most other combat sports, a fist is made before impact onto the target. Tensing the muscles at contact has been linked to reducing energy losses from soft tissue motion by up to 50% (Richards, 1997). The ability to make a ‘power grip’ therefore becomes essential in the terminal phase of a shot. Inability to make this grip due to weakness or pathology can result in the reduced ability to create a tense fist on impact, leading to potential damage at the hand-wrist.

Strength has been defined as the capacity of a muscle or group of muscles to bring force to bear on the environment (Bohannon, 1987). Power grip is one of the three main grasping patterns described for the hand-wrist and is the ability to close a hand with the thumb in opposition to all other fingers together (Goodson, et al., 2007; Landsmeer, 1962). The power grip can be measured as a maximum voluntary force (MVC) of the hand-wrist by using a dynamometer (Gatt et al., 2018; Bohannon., 2001; Schlüssel et al., 2008).

Over a period of 5 years (2010-2014), hand grip MVC measured using the Takei dynamometer was introduced to assess hand-wrist function in the GB Boxing squad (Gatt et al., 2018). The results from this study indicate that when injuries occurred at the hand and wrist, MVC reduced by a mean difference of 40.2% ($p<0.05$) and 32.6% ($p<0.05$) respectively when comparing the results to previously collated baseline measures before injury. The results indicate that in the presence of pathology hand-wrist function, measured through MVC, is altered.

When a boxer is weak or injured, having an altered grip strength, even in the absence of pain, has been considered as a risk factor for deterioration of the condition due to a potential loss of active stability on impact (Gatt et al., 2018). The effect of MVC on wrist stability during impact has however not been investigated in a sport like boxing. Beyond the effect of MVC on providing dynamic stability, the role of bandaging techniques requires consideration. Apart from providing a passive stability role, bandaging the hand-wrist region can likely affect dynamic stability. The effects of bandaging techniques will be discussed in Section 2.6 and Chapter 6.

2.6 The Effects of Bandaging Techniques on Wrist Stability in Boxing

Removable braces at the wrist have been assessed in various activities and sports, with reduced peak forces, increase in time to peak wrist angle, and reduced motion observed under impact (Leslie et al., 2023; Adams et al, 2021; Burkhart and Andrews, 2010; Hwang et al., 2006; Michel et al., 2013). Removable braces, although allowable in training, are currently not sanctioned in competition in either professional or amateur style boxing. Rigid tape, which offers a less rigid structure than braces, is however allowed in all professional style and some amateur style competitions. However, the effects of rigid tape on the movement of the wrist during punching have not been assessed.

When tape was added to the ankle, moments at this joint were significantly reduced during jump landing activities (Sato et al., 2019). Sato et al. (2019) observed reductions in both joint ROM and time to peak angle on inversion motions when tape was added to the ankle. Since ankle lateral ligament sprains mainly occur due to inversion mechanism, adding tape after an injury could reduce forces acting on the ligament allowing return to activities with less risk of reinjury. Adding tape to a healthy ankle could also act as a prophylaxis, by decreasing the inversion moments acting on the joint. However, taping healthy ankles is not common practice. Bandaging at the hand-wrist region, as a prophylaxis for injuries, is a common practice amongst boxers although adding tape to the bandage is less common. Taping is typically used by professional boxers, rather than amateur boxers, as it is a practice used in competition. Similar to an ankle injury, taping around the wrist is commonly used after an injury. This approach post injury enables a reduction in symptoms, whilst allowing the athlete to feel the joint as more secure (i.e., stable) when returning to their sporting activities. Conversely to the ankle however, no studies prior to this programme of research (Chapter 6) assessed wrist kinematics on impact in boxing, so the effect of taping at the hand-wrist region had not been quantified.

A boxer attempts to prevent injuries at the hand-wrist in both training and competition by adequately bandaging these areas to provide more stable joints. Over the period 2010 till current, the physiotherapy services at GB Boxing introduced novel bandaging techniques in training (Figure 2.11a), as compared to traditional common practice (Figure 2.11b). The aim was to reduce the risk of hand-wrist injuries by improving wrist joint stability. The main difference in technique was the introduction of rigid tape (Figure 2.11a), aimed at reducing wrist motion, specifically FLEX.

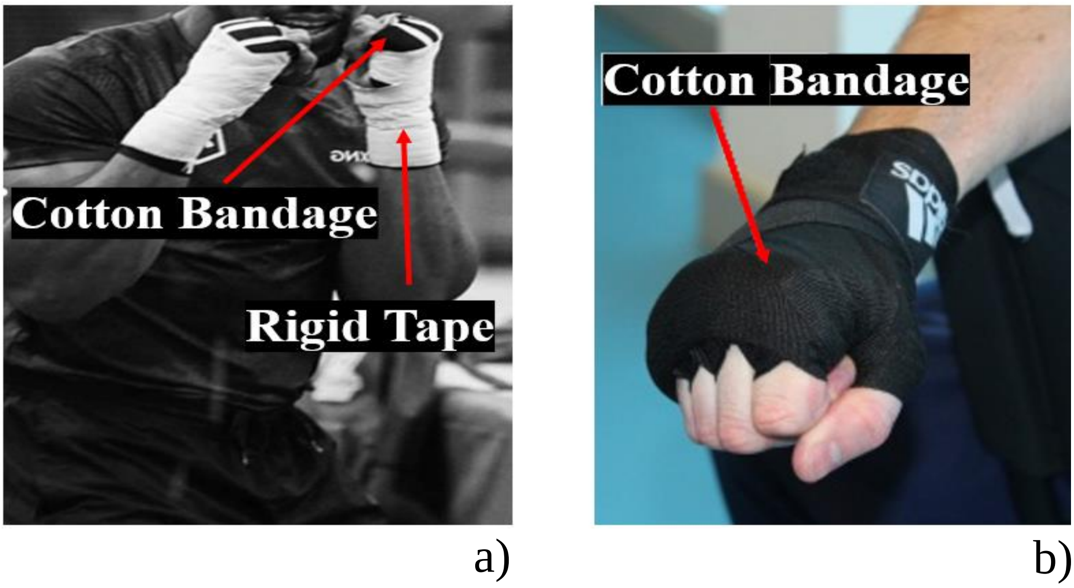


Figure 2.11: Bandaging techniques with and without use of rigid tape with; a) GB training approach using a combination of 4.5m cotton bandage and use of rigid tape, and b) a traditional training approach using only a 4.5m cotton bandage.

Surveillance data, over the period 2010 to current at GB Boxing, showed that hand-wrist injuries squad considerably improved (Loosemore et al., 2017). Loosemore et al., (2017) observed that from 2005 to 2009, injuries recorded at the hand-wrist had a mean of 49.6 days lost for training. When compared to the period 2010 to 2012, when the new bandaging technique was introduced, hand-wrist injuries reduced to a mean of 29.5 days lost for training. It was notable that the addition of rigid tape was having a positive effect at the hand-wrist, as this was the main factor introduced at the time. It was however not possible to quantify whether the rigid tape was affecting wrist motion, as this was not measured. Caution is also required when inferring that only one factor influenced these injury rates across these periods, considering that multiple factors can affect injuries (Table 2.2; Bahr and Holme, 2003; Bahr and Krosshaug, 2005). Changes in training volume, competition schedules, boxers joining/leaving the programme, and other factors could have influenced these changes in injury severity rates. Subjective information from the boxers however, indicated the wrist felt more ‘stable’ when adding rigid tape to bandages. Quantifying the potential effects of rigid tape on wrist kinematics in boxing is therefore warranted, especially at this elite level of participation.

Bandaging techniques in amateur style boxing, to protect the hand-wrist from injuries, have developed allowing more material in competition (International Boxing Association, 2023). Although the permitted cotton bandage material length has increased from 2.5 to 4.5 m, it does not appear to provide the same support as observed in professional style boxing, where rigid tape is allowed across all formats. Rules in amateur style competition limit the use of rigid tape, which is often used in sports to improve support and stability at joints (Kim et al., 2020; Purcell et al., 2009; Sato et al., 2019). In training, there are no limitations ensuring that boxers can be bandaged with as much rigid tape as possible, suffice the hand-wrist region fits comfortably inside the glove.

Between 2005 and 2012, the exposure rate of hand-wrist injuries in competition on the Great Britain squad was observed as 347 injuries /1000 hrs (Loosemore et al., 2017). The competition formats in these studies used bandaging only techniques (i.e., no tape). In a later period, 2016 to 2021, the exposure rate for hand-wrist injuries in competition was observed as 183 injuries per 1000 hrs (Saunders, 2022). The competition formats from this period utilised both bandaging only or professional style which combines rigid tape. The inclusion of rigid tape in competition could therefore have influenced this reduction in hand-wrist injury exposure rates in competition. CMC injury rates were also lower between 2016 and 2021 (n = 14) than between 2005 and 2012 (n=37). The rapid and forceful nature of ballistic stretching, exceeding the extensibility limits of soft tissue structures are believed to result in injury (Davis et al., 2005; Harris, 1969). Ballistic stretching forces the limb into extreme positions, where anatomical structures might have not adapted to be in. A factor why an injury could occur is due to the movement happening too quickly for the neuromuscular system to actively control it. Taping applied to bandaging at the hand-wrist, especially in competition, could therefore reduce angular moments, as observed in other dynamic situations where tape has been applied (Sato et al., 2019).

As mentioned, the rate of exposure per 1000 hrs was less between 2016 and 2021 as compared to 2005 and 2012, 183 injuries and 347 injuries respectively, however, the average days lost per CMC injury were more, 110 days and 54 days respectively

(Saunders, 2022; Loosemore et al., 2017). Taping, applied to bandaging, was used more in training during 2016 to 2021 when compared with the 2005 to 2012 period. Of note, taping in GB training was introduced in 2010. An important consideration could therefore be an active adaptation of the hand-wrist to training. This adaptation, possibly due to increased protection in training, could have led to more severe injuries in competition, where the level of protection was considerably less. Active adaptation from taping is discussed further in Chapters 6 and 7.

2.7 Measuring Wrist Kinematics on Impact in Boxing

Identifying a method to assess wrist kinematics *in vivo*, without affecting the ecological validity of the studies conducted, was an important component of this programme of research. Ecological validity is the degree to which the behaviours observed and recorded in a study reflect those that occur in natural settings (Brewer, 2000). The aim was to use elite boxers throwing shots in their familiar environment at the national training centre, using familiar equipment.

2.7.1 Identifying Wrist Kinematic Methodologies Applicable to Boxing

2.7.1.1 Reflective Surface Markers

Studies investigating wrist kinematics during activities of daily living have used reflective surface markers (Murgia et al., 2004; Su et al., 2005; van Andel et al., 2008). Surface markers motion analysis is a technique used to track the movement of the body by placing reflective markers on specific anatomical landmarks on the skin. The markers are filmed, with cameras, and tracked in software that captures their temporal position in three-dimensions. In a similar manner, studies investigating the kinematics of the upper limb in boxing are available, with results on the ROM occurring at the shoulder and elbow joints, but not the wrist (Piorkowski, Lees and Barton, 2011; Whiting, Gregor and Finerman, 1988). These studies used reflective surface markers and camera-based motion capture systems, with the results interpreted using Cardan angles, a widely described approach (Coburn, Upal and Crisco, 2007; Piorkowski, Lees and Barton, 2011; Rab, Petuskey and Bagley, 2002; Roux et al., 2002; Schmidt et al., 1999; Whiting Gregor and Finerman, 1988; Wu et al., 2005). In boxing, however, using reflective surface markers is unfeasible as bandages and gloves cover the hand and wrist surface. Placing markers on the glove would also not work, as the glove would distort differently on impact to the underlying wrist joint.

2.7.1.2 Electro-goniometer and Electromagnetic Tracking Systems

Other equipment to measure wrist motion include electro-goniometers or electromagnetic tracking systems (Table 2.5). An advantage of both these systems, over optical tracking systems, is they do not require direct line-of-sight to sensors placed on the skin. Boxers would only not wear gloves when shadowing (no impact training), whereas all other forms of training would require gloves for protection.

Electrogoniometers are devices used to measure joint angles electronically. They are commonly used in research and clinical settings to quantify joint ROM and movement patterns. The protractor, typically used in a traditional goniometer as can be found in clinical practice, is replaced by a potentiometer positioned over the centre of rotation-

Table 2.5: Studies using Electrogoniometers and Electromagnetic Tracking Systems for measuring wrist kinematics.

AUTHORS	TYPE OF STUDY	TYPE OF SYSTEM UTILISED
(Aizawa et al., 2013)	20 healthy adults used to measure three-dimensional motions of the shoulder, elbow, forearm, and wrist during active joint motion tasks of the upper extremity	Electromagnetic tracking system (FASTRAK)
Asundi, Johnson and Dennerlein, 2011	20 participants completed a standard computer task at the two workstation configurations.	Twin axis goniometers
(Greenwald et al., 2013)	20 skiers using lab based and field-based studies - development of a specialised splint	Electrodes are placed inside gloves/mittens measuring both kinetics and kinematics.
(Fagarasanu et al., 2004)	20 subjects used to determine the forearm muscles activity in different wrist deviated positions and wrist neutral zone	A custom-made calibrated electro-goniometer
(Johnson, Jonsson and Hagberg, 2002)	8 subjects moving their wrists within specified ranges of motion.	single-transducer biaxial goniometer & a two-transducer, biaxial goniometer
(Jonsson and Johnson, 2001)	8 subjects placed in 20 different wrist postures	single-transducer biaxial goniometer & a two-transducer, biaxial goniometer
(Nelson, Treaster and Marras, 2000)	15 experienced typists during typing activities	Two thin metal strips connected with a rotary potentiometer which measured the angle between the 2 segments
(Ryu et al., 1991)	40 normal subjects used to determine the ideal range of motion required to perform activities of daily living	Biaxial wrist electro-goniometer
(Short et al., 1995)	6 fresh cadaver arms, investigate the role of the Scapholunate interosseous ligament in carpal stability	Polhemus (Polhemus Inc., Colchester, VT) 3 SPACE tracking device
(Short et al., 2002)	8 right, fresh-frozen cadaver upper extremities, used to assess kinematics of the wrist	Polhemus Fastrak electromagnetic sensors
(Veeger et al., 1997)	5 upper extremity specimens provide parameters for the development of a musculoskeletal model of the upper extremity.	A magnetic position and orientation tracking system (3 Space Iso-track System (Polhemus)

-of the joint being monitored. The goniometers are connected to a small electronic device that records the angle of the joint in real-time. This device can be either a stand-alone unit or integrated into a computer system for data analysis. Electrogoniometers have been used to measure wrist motions during activities of daily living (Asundi, Johnson and Dennerlein, 2011; Fagarasanu, Kumar and Narayan, 2004), and in snowboarding to assess wrist extension during falls (Greenwald, Simpson and Michel, 2013). Snowboarding is another sport where wrist injuries are common, and gloves worn. Electrogoniometers offer an advantage over traditional manual goniometry, namely the measurement of joint angles during dynamic sport movements.

Electrogoniometers have some limitations, including the need for careful placement of the sensors on the wrist joint anatomy. Electrogoniometers are also prone to measurement errors particularly due to *crosstalk* (Buchholz and Wellman, 1997; Johnson, Jonsson and Hagberg, 2002), so equipment selection is important (Hansson et al., 1996), as is precise alignment with the wrist joint anatomy. Further, electrogoniometers can incur damage from high and repetitive forces, an important consideration with boxing (Smith et al., 2000).

Electromagnetic tracking systems are devices which use an electromagnetic field generator to detect the position of electromagnetic sensors (Sorriento et al., 2020). The sensors are attached to the object of interest and an electromagnetic field generator is used to create a surrounding magnetic field. As the object, and hence sensors, moves within the magnetic field, changes within the magnetic field are detected and sensors transmit this information to a computer, calculating the object's position and orientation. As mentioned, one of the main advantages of this system is it does not require direct line-of-sight to collect data (Sorriento et al., 2020). The sensors are also non-invasive, making them suitable for use in various dynamic settings, including sports. Electromagnetic sensors have also been described in the assessment of wrist motions, as well as other joints of the human body (Aizawa et al., 2013; Delorme, Tavoularis and Lamontagne, 2005; Heneghan et al., 2009; van Andel et al., 2008; Veeger et al., 1997).

Electromagnetic sensors offer other advantages over other motion tracking technologies, including high accuracy, real-time tracking, and the ability to track multiple objects simultaneously (Golestani and Moghaddam, 2021; Parent, 2012; Yaniv et al., 2009). Considering accuracy, electromagnetic tracking systems have been shown to be comparable to optical tracking systems, with differences in technical accuracies considered marginal (Koivukangas, Katisko and Koivukangas, 2013). In a study comparing an electromagnetic tracking system with radiographic measurements for in vivo elbow ROM in different angles, which is a “gold standard” for accuracy, high accuracy was observed (Yamaura et al., 2022). In this study, the error between the mean measurement angle with the electromagnetic tracking systems and the reference device subseeded 1.7°, with a Pearson's correlation coefficient was 0.999 ($p < 0.0001$), indicating high accuracy (Yamaura et al., 2022).

Electrogoniometers, specifically at the wrist, have shown error measurements of 7.1 to 9.7 degrees for FLEX-EXT (McHugh et al., 2020; Marshall, Mozrall and Shealy, 1999; Buchholz and Wellman; 1997) and 5.6 to 9.7 degrees for RD-UD (Marshall, Mozrall, and Shealy, 1999; Buchholz and Wellman; 1997), indicating lower accuracy than electromagnetic sensors. Marshall and colleagues (1999) suggested that changes to the design may prevent the occurrence of zero drift and crosstalk error observed in their study, when using electrogoniometers. However, accurate anatomical placement and crosstalk are always factors which can influence accuracy as compared to electromagnetic sensors, where these factors are not observed. Sensors used in electromagnetic tracking systems do not require precise alignment as those used in electrogoniometers (Aizawa et al., 2013; Heneghan et al., 2009), although careful selection and identification of reference points on anatomical landmarks is required.

Electromagnetic tracking systems are affected by ferromagnetic materials which can disturb the local magnetic field, and therefore the position and orientation estimation (Roetenberg, Baten and Veltink, 2007), but a simple solution is to avoid using them near large metal objects. Bull and colleagues (1998) observed mild steel to have significant detrimental effects on the accuracy of the system, when within 150 mm of the transmitter or receiver, whereas stainless steel did not affect accuracy. Therefore, electromagnetic tracking systems are potentially viable for assessing wrist kinematics in boxing during boxing shots on impact, yet the accuracy and repeatability have not been reported. Further discussion on accuracy, and repeatability, of electromagnetic tracking systems is provided in Chapter 4.

Electromagnetic tracking systems can be either wired or wireless. Wireless systems are commonly used in motion tracking and object detection applications where it may be unfeasible or unpractical to use wired sensors. Wireless electromagnetic sensors could offer advantages over wired sensors, mainly the ability to assess wrist kinematics during more dynamic actions, like sparring and competition. However, in both sparring and competition, boxers typically come into close contact (i.e., grappling). The wires from both wired and wireless could therefore become dislodged making this technology unfeasible. Wireless electromagnetic sensors also have other limitations, including the potential for signal loss or interference from other electromagnetic devices or materials, limited range and battery life, and the need for careful calibration and setup to ensure accurate and reliable data.

2.7.1.3 Inertial Sensors

Inertial sensors can be easy to use and provide real time feedback. Inertial sensors are an emerging technology in boxing, used to measure shot velocities and quantify fatigue during training (Kimm and Thiel, 2015; Shepherd, Thiel, and Espinosa, 2017; Worsey et al., 2019). Inertial sensors are electronic sensors that measure the acceleration and rotational movement of an object with respect to a specific frame of reference. These sensors typically consist of accelerometers and gyroscopes, working together to measure linear and angular motion. Accelerometers measure the accelerations acting on an object in three dimensions, allowing for the measurement of linear motion along one or several axes. Gyroscopes measure the angular velocity and orientation of an object in three dimensions, allowing measurement of rotational motion including changes in orientation and angular velocity. Inertial sensors are used in various applications, including navigation systems, robotics, virtual reality, and sports performance analysis. However, inertial sensors have limitations, including errors that can accumulate over time, leading to inaccuracies in position and orientation data. This is known as drift and can be corrected by periodically resetting the sensors to a known reference point. Inertial sensors are also sensitive to external forces, such as vibrations or magnetic fields, which can interfere with the accuracy of the measurements.

Angle measurement errors, from inertial sensors, observed during data collection comprise mainly technical problems such as transmission lag (Chen et al., 2015). The signals can also be contaminated by noise introduced in the acceleration or magnetic signals, nature of the sensors, or human motion artefacts derived from sensor placement (Chen, et al., 2015; López-Nava and Muñoz-Meléndez, 2016). Wearable sensors also need to handle joints involving more than one degree-of-freedom as multi-plane movements not only require the capability of tracking motion in different axes, but also the ability of removing bias that the movement in a different axis might have on a tracked axis (Huang et al., 2016; Wu et al., 2005).

2.7.1.4 Equipment Selected for the Wrist Kinematic Methodology

Wired electromagnetic tracking systems were deemed the most applicable option for investigating wrist kinematics during boxing. This decision was made mainly on; a) no direct line-of-vision required from the sensors to the source box, b) no precise application required on the upper limb anatomy, c) reduced potential for errors due to crosstalk and equipment failure, albeit electromagnetic disturbance had to be accounted for, and d) good level of accuracy noted in various studies as compared to other equipment. The main limitations noted were a) electromagnetic disturbance meaning that the environments had to be void of large ferrous materials, within specific distances of the equipment, and b) the sensors were wired limiting motion to more controlled conditions than highly dynamic conditions (i.e., sparring). However, this wired equipment suited the intended design of the studies in this programme of research (Chapter 3).

2.8 Chapter Conclusion

The hand-wrist region incurs the highest injury prevalence and incidence rates in boxing compared to other regions, with CMC joints providing the highest number of days lost than any other injury. Wrist motion on impact appears to be an important factor linked to CMC injuries, as well as other injuries occurring at the hand-wrist. The proposed motion occurring when CMC injuries occur is forced FLEX. However, wrist motion on impact has not been quantified. It is therefore unclear whether FLEX is a normal mechanism occurring at the wrist on impact in boxing, and what magnitude typically occurs in certain activities, like bag training. Further, FLEX naturally occurs with UD (i.e., DTM) due to the axis of motion occurring at the MiC joint. DTM has been observed in sporting and occupational studies. So, it is unclear should FLEX occur on impact whether UD would also be observed. DTM on impact, especially ulnoflexion, could likely explain why certain types of hand injuries are observed in boxing, namely second-to-third CMC injuries.

There are various punches which can be thrown with either lead or back hand. Different punches can mainly be divided into straight arm or bent arm shots. Bent arm shots generate the higher terminal velocities compared to straight arm shots, with the latter being delivered faster than the former. Although not previously considered, these differences in shot types could likely result in differences in magnitude of wrist motion on impact. As wrist motion on impact has not been quantified in boxing, or any other combat sport, it is unclear whether differences in shots will have significant differences on these motions.

In boxing, bandaging the hand-wrist region to reduce the risk of injuries is common practice, however, the effect of bandaging is not known. Further, in both training and competition scenarios adding rigid tape, to further reduce wrist motion on impact, is a global practice which has been done historically. Adding rigid tape to a bandage would be expected to reduce wrist motion on impact, compared to bandage only, due to the tensile properties of these materials. However, only a few studies have assessed the effects of rigid tape, in other joints, during dynamic situations. A few studies at the wrist, in non-dynamic situations, have been performed. The results of these studies, as discussed in this chapter, show that rigid tape has a significant effect in reducing joint motions. The effect of rigid taping on wrist motion in boxing is therefore unclear, however, the inference from wider studies is that a reduction in wrist motion should occur. Appropriate studies are required to better understand the possible influence of rigid tape on wrist motion during dynamic conditions like punching.

To quantify wrist motion on impact, and the effects of shot types and bandaging techniques on wrist motion, a valid and reliable methodology is required. To date various studies have assessed upper limb kinematics in boxing, with the wrist not considered. A reason for omitting the wrist in upper limb kinematic studies in boxing is likely due to the methodology used in these studies. Optical tracking systems were used, requiring direct line-of-sight from the reflective markers to the motion capture cameras. However, boxing gloves cover the wrists when shots are thrown against a target, with other systems likely more suited for wrist motion analysis. In this chapter, wired electromagnetic tracking systems were identified as the most plausible methodology for assessing wrist kinematics on impact in boxing. These systems have been proven to be accurate and reliable in measuring ROM, yet this system has not been previously considered for use in boxing. Assessing the accuracy and reliability of this system, to measure wrist motion, in boxing it therefore important, ensuring the feasibility of future studies in this sport.

This programme of research will there present a logical approach towards better understanding current gaps of knowledge in wrist kinematics on impact in boxing. Chapters 3 and 4 will focus on the methodology identified, ensuring the validity and reliability of the system meet the criteria set for the system chosen, to be utilised in future studies. Chapter 5 and 6 will focus on quantifying wrist motion on impact, and understanding how shot types and bandaging techniques influence changes in wrist motion on impact. The practical implications from the results obtained from these chapters will be discussed in Chapter 7, with a consideration towards what knowledge has been obtained, limitations, and future research which should be considered following this programme of research.

3.0 Methodology of the Electromagnetic Tracking System

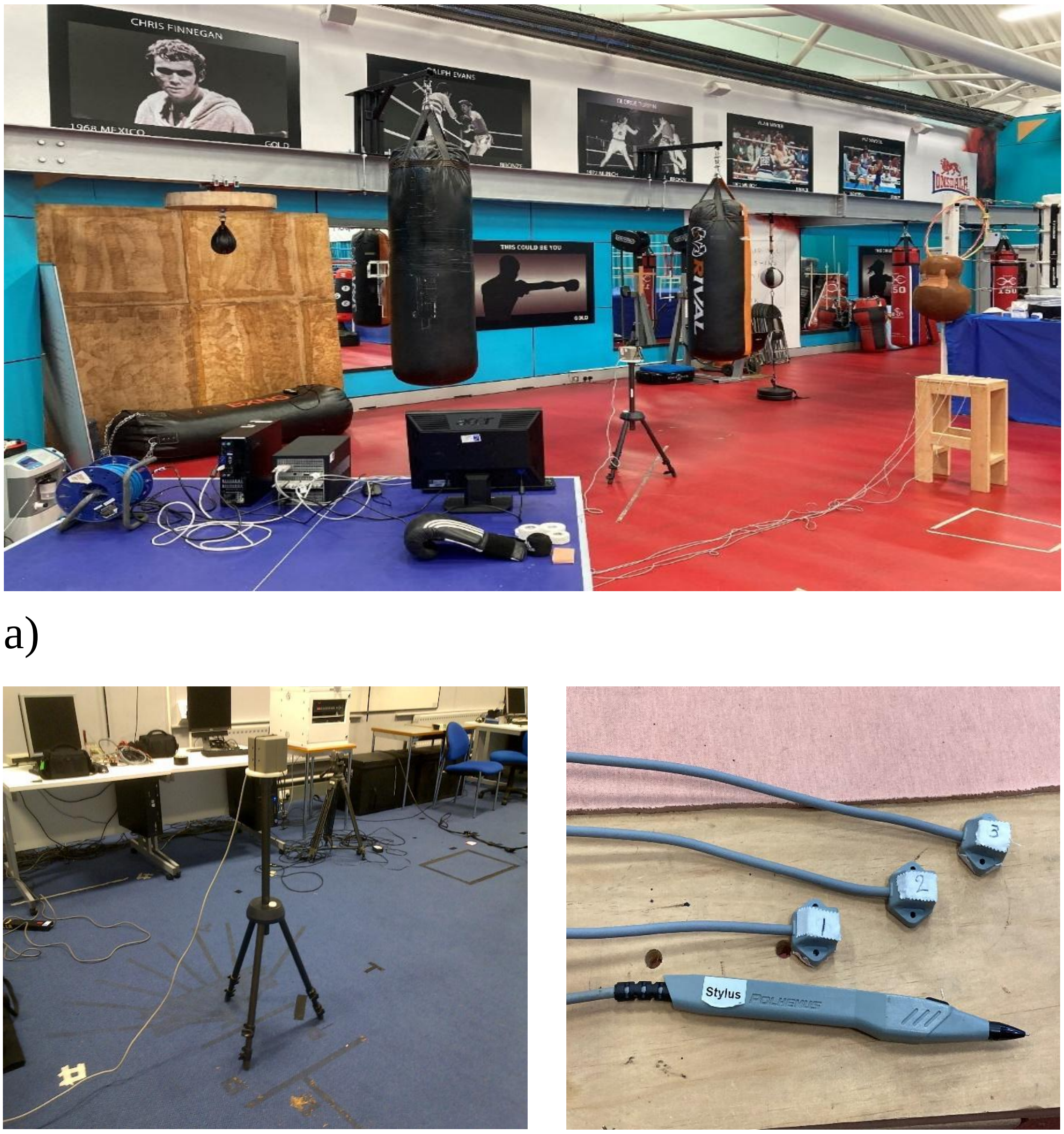
This chapter provides an outline of the pilot testing performed and how problems identified were overcome. Further, a stepwise approach is provided to testing and analysis procedures, ensuring future replicability of methodology. The methodology described in this chapter was used in the studies conducted in this programme of research (Chapters 4 to 6).

3.1 Equipment and Set-up of the Electromagnetic Sensors

Various equipment (Figure 3.1) was used for the studies conducted (Chapters 4 to 6):

- Portable Monitor
- PC tower and 1x Polhemus Liberty system electronics unit (SEU)
- Extension and Connecting Cables
- 4× Electromagnetic sensors (stylus pen plus three receivers)
- Electromagnetic source box plus stand
- Surrogate hand-forearm model
- Wooden rig

A Polhemus Liberty electromagnetic tracking system (Polhemus, Colchester, VT, USA), with 6-degree-of-freedom (DoF) position and orientation receivers, was used to measure kinematic data at the maximum available sampling rate of 240 Hz. This frequency was selected based on previous studies investigating upper limb kinematics in boxing, where sampling rates used were between 125 to 250 Hz (Bergün et al., 2018; 2017; Cheraghi et al., 2014; Lenetsky, et al., 2018; Whiting, Gregor and Finerman, 1988). The system used consisted of a source box, three receivers and a stylus (Figure 3.1). More receivers can be used with the system, however, for the proposed studies the areas required were the upper arm, forearm, and hand of the left upper extremity of each participant.



a)

b)

c)

Figure 3.1: Electromagnetic tracking system set-up with; a) equipment set-up in the GB Boxing Gym, b) source box and stand, and c) stylus pen used to digitise virtual markers on the participants and the three receivers used for attaching to the hand, forearm, and arm segments of the upper limb.

For both the piloting stage, and the first study investigating the accuracy and repeatability of methods (Chapter 4), a surrogate wrist model was used. The surrogate wrist model was obtained from a previous study (Adams et al., 2021), 3D printed in polyamide using dimension from EN 14120; 2003 on wrist protectors European Committee for Standardization, 2003).

3.2 Placement of the Electromagnetic Receivers

Two and three receivers were respectively fixed to the surrogate (Figure 3.2) and participants (Figure 3.3) of the studies. Two electromagnetic tracking system receivers were attached to the wrist surrogate allowing for one DoF (FLEX-EXT). One receiver was attached to the hand (mobile component), whilst another receiver was attached at the forearm (fixed component) using double-sided adhesive tape and zinc oxide tape (W: 1.25 cm). Segment coordinate systems were defined, using a digital stylus, based on eight non-anatomical landmarks for the surrogate (Figure 3.2); four for the moving component (hand) and four for the non-mobile component (forearm).

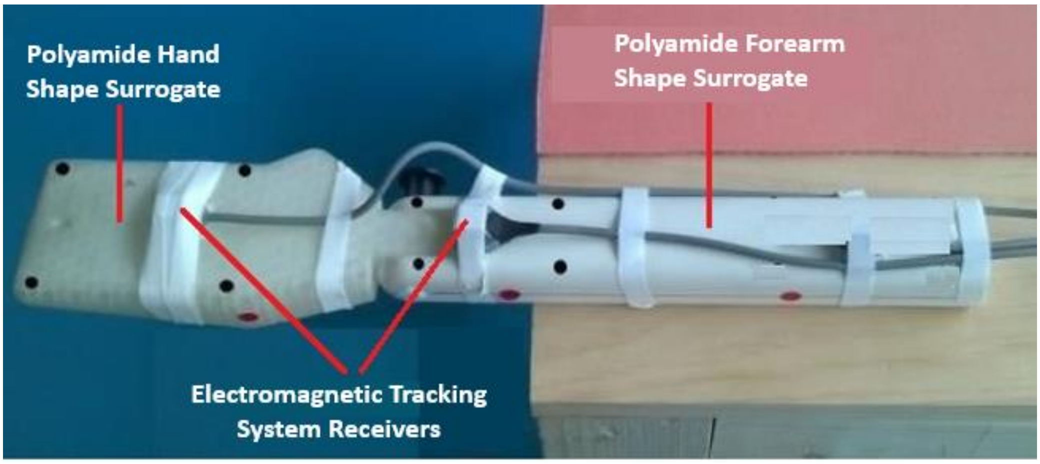


Figure 3.2: Electromagnetic tracking system placement for the surrogate hand-wrist model. Receivers (grey ×2), virtual markers (black x8), and self-adhesive markers (red ×3). *Figure source from Gatt, Allen and Wheat (2020).*

Figure 3.3: Electromagnetic tracking system placement for the in-vivo upper limb region. Receivers (grey ×3) and virtual markers (Black x11) placement for the upper limb. Joint centre is dotted (shoulder joint). N.B. The virtual markers were digitised more medial and lateral for the actual study than observed on this figure. The current placement is provided as a visual reference of the markers. *Figure source from Gatt, Allen and Wheat (2020).*

Three electromagnetic tracking system receivers were secured to the left upper arm, forearm and hand of the participants using double-sided adhesive tape, zinc oxide tape (W: 1.25 cm), and elastic cohesive bandaging (W: 2.5 cm). Bandaging materials placed around the hand-wrist region, discussed further on in this chapter, ensured the receivers were additionally secured when participants placed their hand-wrist region inside the gloves for impact testing. At the hand and forearm, closed cell latex foam squares (Hapla Swanfoam, Cuxson Gerrard and Co. Ltd.) were used as padding between the plastic receivers and bone prominence (L: 2.5 cm × W: 2.5 cm × H: 0.3 cm).

Segment coordinate systems were defined, using a digital stylus, based on 11 anatomical landmarks for the participants (Figure 3.3). The anatomical landmarks were *Hand*; Head of 2nd Metacarpal Bone, Base of 2nd Metacarpal Bone, Head of 5th Metacarpal Bone, Base of 5th Metacarpal bone, *Forearm*; Styloid Process of Radius, 7 cm proximal to Styloid process of Radius, Head of Ulna, 7 cm proximal to Head of Ulna, and *Arm;* Medial Epicondyle of Humerus, Lateral Epicondyle of Humerus, Mid-Acromion of Scapula.

Segment coordinate systems were embedded in the left upper limb segments, defined based on the location of the anatomical markers such that the x-, y- and z-axis were medio-lateral, anterio-posterior, and longitudinal, respectively. The orientation of the hand relative to the wrist was defined using Cardan angles (xyz rotation sequence), to determine wrist FLEX-EXT and UD-RD angles (Metcalf et al., 2008; Murgia et al., 2004; Rab, Petuskey and Bagley, 2002; Roux et al., 2002; Schmidt et al., 1999; Wu et al., 2005).

3.3 Piloting Stages for Testing of the Methodology

These next sections will discuss any relevant factors met during the piloting stage and how any areas of concern were overcome.

3.3.1 Surrogate Model for the Static Testing Condition

Piloting was performed initially using the surrogate model to assess the feasibility and effectiveness of the research design, including the experimental setup, data collection methods, sampling techniques, and statistical analyses. Any flaws or limitations in the design were identified before considering use on human participants. During the pilot testing, to ensure no electromagnetic interference from the ground, it was identified that the surrogate would be best placed on a stand. A wooden rig (L: 45 cm × W: 14 cm × H: 84 cm) was therefore constructed and used for the static testing using the hand-forearm surrogate (Figure 3.4). To eliminate the possibility of interference from by ferrous materials, the instructions from the manufacturer of the electromagnetic system was followed. The instructions suggest placing the sensors at a distance from the distorter of more than three times the distance between the sensors (i.e., the receivers and source box). Further, the electromagnetic tracking system has a visible detecting system when interference is present (i.e., a green light located on the SEU turns red). Finally, when interference was present the sensors' location, displayed on the portable monitor, were observed to be in the wrong position compared to their actual physical location. When these sensors were physically moved, they appeared to move erratically on the portable monitor. Assessing for interference was performed during the set-up of every participant, in all the studies conducted.

The ferrous metal (i.e., stainless steel) *thread* and *nut* attaching the surrogate hand to the forearm segment provided electromagnetic disturbance. Non-ferrous alternatives (i.e., nylon) were therefore identified (Figure 3.4), ensuring no ferrous materials were in the proximity of the receivers.

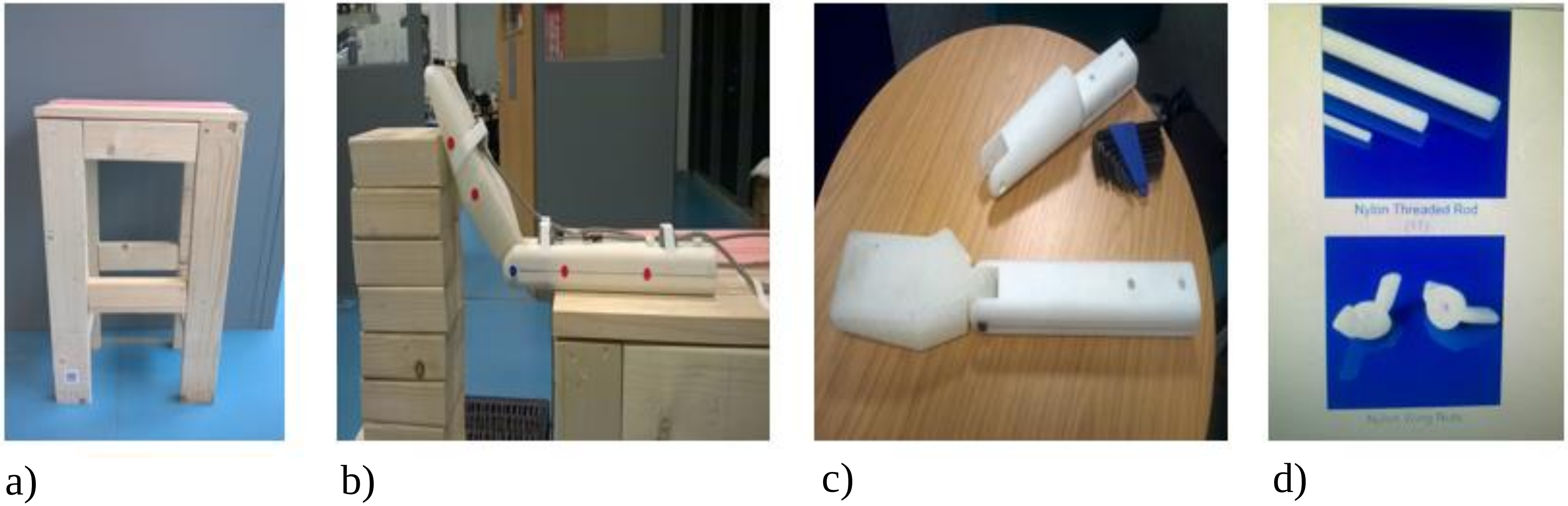


Figure 3.4: Rig and surrogate model used during piloting stages with; a) constructed wooden rig, b) trialling of different angles, sensor placement, and cable securing methods, c) trialling of different components for the surrogate model, and d) identification non-ferrous (i.e., nylon) to replace ferrous (i.e., metal) components.

3.3.2 Participant Testing for the Quasistatic and Impact Testing Conditions

Following the work with the surrogate model, further piloting was conducted with athletes at the GB Boxing programme (Figure 3.5). Logistical and practical challenges associated with data collection such as time constraints, equipment malfunctions, or procedural issues were assessed. Further, it allowed understanding the feasibility of recruiting an adequate number of participants, within the desired period of research.

For both quasistatic and impact conditions the transmitter (source box) was elevated 1 m off the ground. In accordance with the manufacturer’s guidelines, this position provided detection of the magnetic signal generated by the transmitter within the hemispherical range radius required for all testing (150 cm).

For the quasistatic, different methods were trialled using no forearm support or some form of support (Figure 3.5). The best methodology identified was having the forearm resting on a stable surface, which is a widely used clinical approach for assessing wrist motion. However, similar to the surrogate testing it was acknowledged that most tables contain some ferrous metals. The wooden rig, previously constructed for the surrogate model, was considered as an alternative and deemed suitable for use in all the studies conducted in this programme of research (Chapters 4-6). A piece of adhesive foam (Swanfoam, L: 38 cm × W: 22.5 cm × H: 0.3 cm) was placed between the forearm of the participants and rig to improve comfort and reduce movement of the forearm during testing.

a) b) c)

Figure 3.5: Piloting stages assessing the quasistatic methodology with participants for wrist kinematics using the electromagnetic tracking system with; a) standing using no support, b) standing using support, and c) seated using support.

Before the first study, it was important to ensure the impact testing mimicked normal conditions for throwing both straight and bent arm shots, improving ecological validity (Brewer, 2000). The target, a boxing bag situated in the GB boxing gym at the English Institute of Sport in Sheffield, was therefore trialled (Figure 3.6). The target area was defined as head height on the boxing bag, for each participant rather than a fixed target. This enabled normal conditions for the shot types selected (Fig. 3.6). The boxing bag is discussed further in this chapter (Section 3.4.2.3). Electromagnetic disturbance was assessed, ensuring no detrimental effect on results present due to any ferrous metals. Placement and securing of the receivers on the boxers also meant ensuring mobility to perform shots without any restriction.

This piloting phase also allowed an opportunity to evaluate the ethical implications of the intended studies, including; participation privacy, informed consent procedures, and any potential harm. To minimise the risk of knuckle injuries during testing, a piece of foam (Hapla Swanfoam, Cuxson Gerrard and Co. Ltd., L: 10 cm x W: 4 cm x H: 0.6 cm) was placed directly over the anterior aspect of metacarpals, as typically used by boxers during training. This material was used for all the studies conducted in this programme of research (Chapters 4 to 6).

Overall, the piloting stage allowed all necessary procedures to be in place, leading to the smooth running of all studies. More detail on the methodologies used in each study are provided in the next sections, including procedures for data collection, conversion, processing, and analysis.


[redacted]
[redacted]

a) b)

Figure 3.6: Piloting stages assessing the methodology for wrist kinematics with the electromagnetic tracking system during impact testing in the GB Boxing gym situated at the Olympic National Centre in Sheffield with two shot types; a) straight arm, and b) bent arm.

3.4 Methodology for the Studies in the Programme of Research

3.4.1 Surrogate Testing

The surrogate model used, in the study conducted in Chapter 4 (Figure 3.4b), was secured onto the rig identified during the pilot stages (Figure 3.4a). The methodology used is described in Chapter 4.

3.4.2 In-Vivo Testing

3.4.2.1 Participants

To be included in the studies, participants were elite level boxers forming part of the National Olympic GB Squad, ranked 3rd in Olympic boxing (Statista, 2022), with no history of upper extremity injury in the three months before recruitment and no current upper extremity symptoms. All participants in the studies were right-arm dominant and Orthodox stance boxers (left-hand leading), with a rationale for selecting Orthodox as compared to Southpaw stance boxers discussed before (Chapter 2). The number of participants chosen, and characteristics, for all the studies are provided in Chapters 4 to 6. All experimental protocols were explained verbally. All participants received written information about the studies and provided informed consent before testing (Appendices).

3.4.2.2 Quasi-Static Testing

For all the studies (Chapters 4 to 6), the forearm was placed on the same rig used for the surrogate testing. The participants started with the left forearm placed in a full pronated position (Figure 3.5c). The wrist joint was positioned in neutral, with a closed fist holding onto a cylindrical plastic handle (L: 12 cm x D: 4 cm), to mimic the functional position of a boxer’s hand when held in a glove. Each participant was asked to fully flex at the wrist, hold the position for three seconds, fully extend at the wrist and again hold still for three seconds. For UD and RD, the same procedure was used with the forearm positioned in mid-pronation. Out of plane movement was limited by instructions provided to participants. All motions were performed three times, with the participants instructed to move only in the requested plane of movement without any deviation.

A commercially available (Adidas®), traditional cotton boxing wrap (L: 450 cm x W: 5 cm), was used to bandage the left hand of each participant using a standard technique (Figure 3.7). This bandage was not used in the quasistatic testing in Chapter 4, due to the requirement for self-adhesive markers on the skin to be visible, and subsequent video analysis. However, bandaging was used during the impact testing condition in this study (Chapter 4). In Chapters 5 and 6, quasistatic testing was performed initially without bandaging to assess total active wrist ROM (TROM) occurring with no bandaging, and then with the bandage on to assess the available active wrist ROM (AROM).

3.4.2.3 Impact Testing

For all the studies (Chapters 4 to 6), the electromagnetic tracking system receivers were fixed to the left upper limb (Figures 3.3 and 3.8) following the same procedure for the quasistatic testing. All the boxers were tested in their training centre using familiar equipment and surroundings, improving ecological validity (Andrade, 2018).

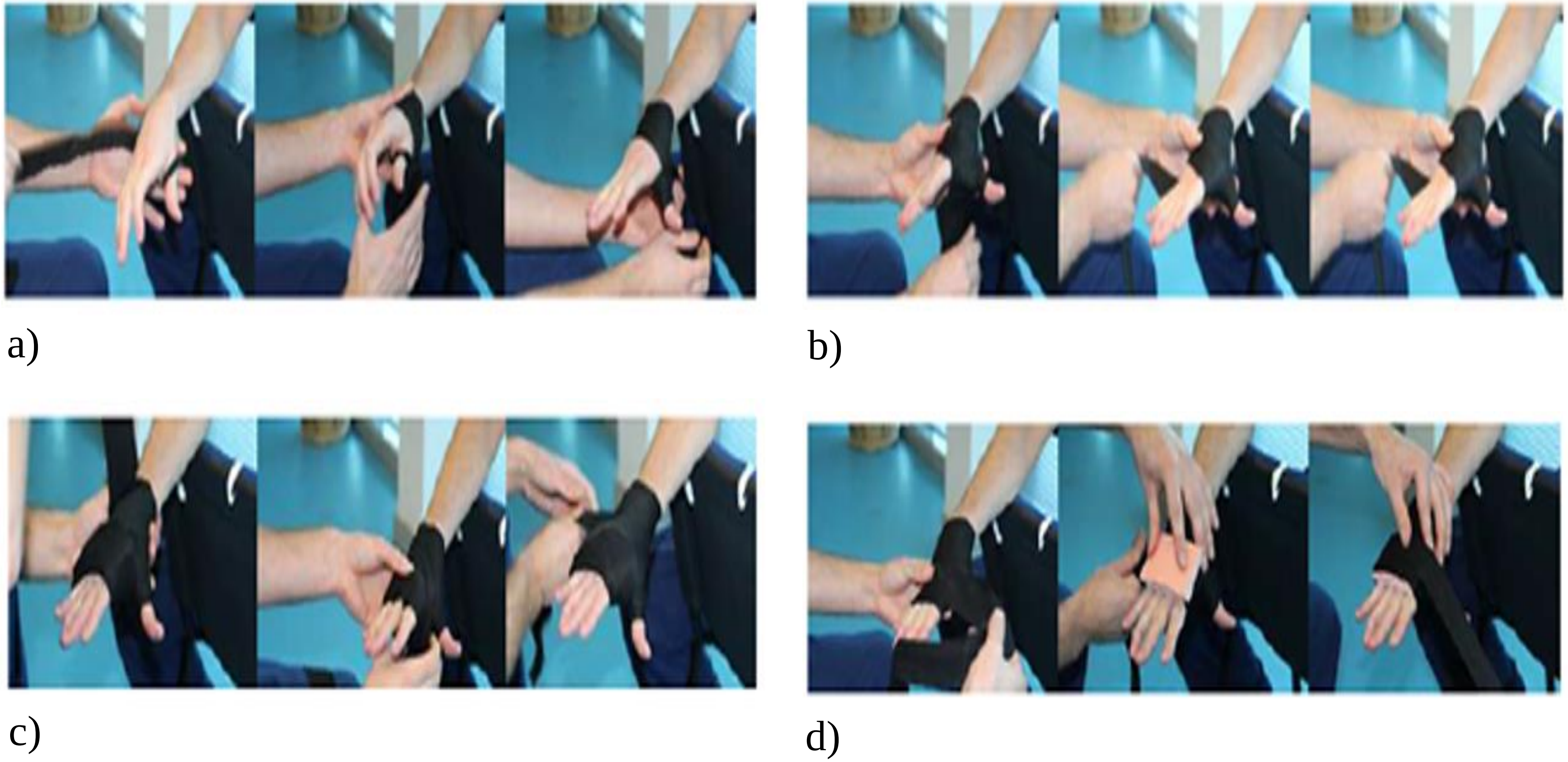


Figure 3.7: Standardised bandaging technique using a 4.5m cotton bandage with a) step one, the hook of the bandage looped around the thumb. The bandage was then wrapped across the front wrist to the back and moved to around the thumb, b) step two, the bandage was directed back around the wrist, coming back between the finger and thumb region. The bandage was then directed towards the knuckles covering them. At this stage the bandage had covered the whole hand-wrist leaving no exposed skin in this region, c) step three, the foam pad was inserted across the knuckles. The bandage was wrapped around the knuckles three times to secure the foam pad, and d**)** S**t**ep four, the bandage was wrapped a few times around the wrist, taking care to cover up to the distal 1/3 of the forearm. *Figure source (Gatt, Allen and Wheat, 2023).*

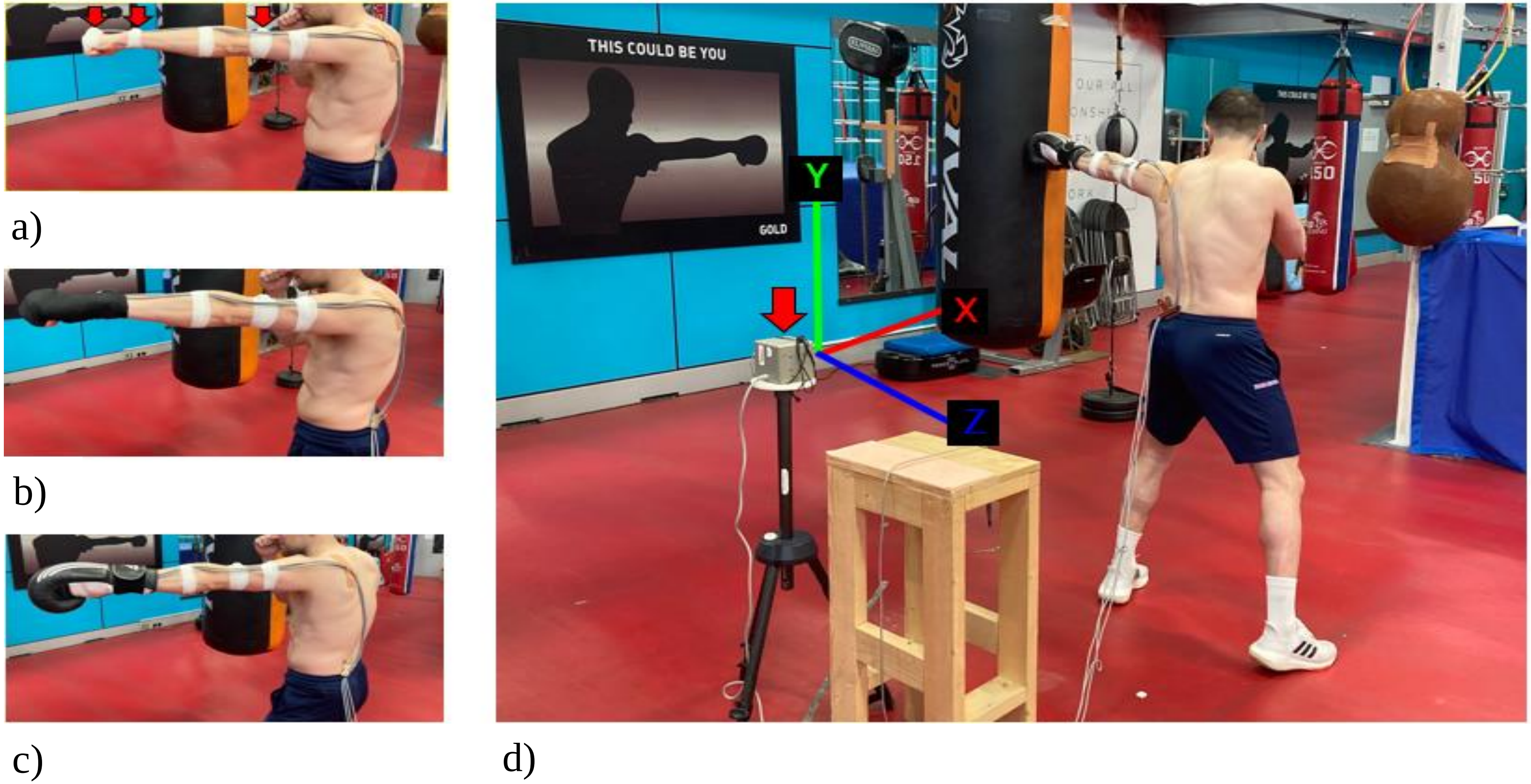


Figure 3.8: Electromagnetic tracking system receiver placement for the impact testing. Receiver placement; a) on the hand and forearm using rigid tape and cohesive bandaging to secure the receivers, with arrows above the arm indicating their anatomical positions, b) with a standard bandage covering the receivers, c) with a boxing glove covering either bandage only or bandage plus tape techniques and receivers, and d) during impact testing on the bag in the boxing gym with an arrow above the source box, and with xyz orientation, indicating the position of the participant relative to the source box. *Figure source adapted from Gatt, Allen and Wheat (2023)*.

For all impact testing (Chapter 4 to 6), a boxing glove (14 oz Adidas), of the correct size, and suitable for the studies performed on training equipment, was worn by each participant covering the hand and forearm receivers (Figure 3.8c). In boxing various glove sizes can be considered with larger sizes (typically up to 18 oz) used in training and smaller sizes (up to 8 oz) used in competition. To ensure the results of the studies were not influenced by a change in glove, the glove size was consistent for all participants and studies. Less glove material likely provides less impact protection and support around the wrist. However, a bigger glove would be heavier on the front than a smaller one, potentially increasing the angular velocity of the wrist on impact. Perkins et al. (2018) conducted research comparing 10 and 16 oz gloves, with the heavier ones producing 4.8% more total energy, along with increased peak forces (26.6 N per kg). Considering that glove rules vary between training and competition, it is certainly an independent variable which should be considered for future studies.

For all the studies, participants were asked to face the target, a hanging boxing bag (Rival heavy bag 91 kg, L: 152 cm × W: 48 cm × D: 0.6 cm) located in the GB boxing gym (Figure 3.8d). This type of bag is commonly used by boxers during training sessions. Boxers adopted their natural orthodox stance when facing the target (Figures 3.6 and 3.8d). Each participant was then asked to throw two types of commonly used shots in boxing with their lead hand; Jab and Hook. Lead straight arm (Jab) shots display the shortest delivery time and lead bent arm (Hook) shots exhibit greater peak fist speed (Stanley et al., 2018), making the choice of shots relevant to the methodology for all the studies.

Participants were asked to throw shots at submaximal intensity, reflective of their normal training behaviour. Most studies, however, typically consider a maximal intensity approach (Dinu and Louis, 2020; Kimm and Thiel, 2015; Whiting, Gregor and Finerman, 1988). Throwing a shot maximally could have reduced the ecological validity of the studies, considering that shots are rarely thrown at maximal intensity during training. On the other hand, it could be expected that injuries occur at maximal effort, combined with terminal ROM. Submaximal shots were chosen for this study to limit the risk of injury to participants.

Jab shots were performed six times, allowing a between-shot break of about three seconds. The 2nd to 5th shots were used for statistical analysis, calculating the mean of trial peaks (Dos'Santos, Comfort and Jones, 2020). The 1st and 6th shot were not analysed, to limit potential errors / inconsistencies from those thrown at the start and end of testing. Boxers performed both shot types in both bandaging conditions in the same session.

3.5 Data Collection and Conversion

Data Collection was performed using an application (C3D Collection) written using a source code editor software (Microsoft Visual Studio C#). Coordinates were written and defined for each receiver in a text document and uploaded onto C3D Collection (Table 3.1 and Figure 3.9). The stylus pen (Figure 3.1) was used to digitise each coordinate, performed with each participant's arm in an anatomical position (i.e., arm by side with hand open, forearm in full supination, elbow in full extension, shoulder in full external rotation). 'Coords' files for each test were then converted to 'C3D' files using an application (Coords2C3DConverter) written using a source code editor software (Microsoft Visual Studio C#). Conversion was required for data processing.

Table 3.1: Segment coordinates with anatomical reference points

SEGMENT	COORDINATE	ANATOMICAL LOCATION
HAND	LKN1	Left First Knuckle (Index finger) - Head of 2nd MC Bone
	LKN4	Left Fourth Knuckle (Pinky finger) - Head of 5th MC Bone
	LMC2	Left Base of 2nd Metacarpal Bone (Index finger)
	LMC5	Left Base of 5th Metacarpal Bone (Pinky finger)
FOREARM	LRST	Left Radius Bone - Styloid Process
	LUST	Left Ulna Bone - Styloid Process
	LRAD	Left Radial Bone - 7cm proximal to Styloid Process
	LULN	Left Ulna Bone - 7cm proximal to Styloid Process
ARM	LLEP	Left Lateral Epicondyle of Humerus
	LMEP	Left Medial Epicondyle of Humerus
	LACR	Mid-Acromion Point of Scapula - Mid-Shoulder

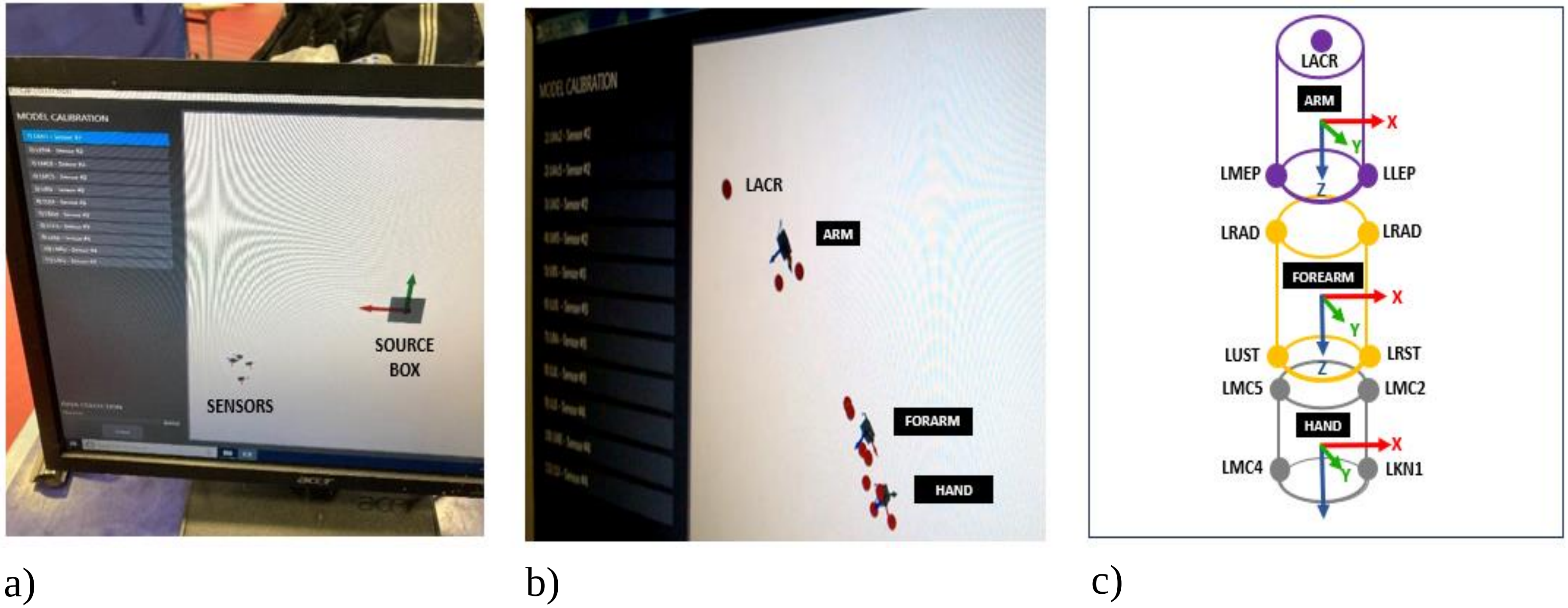


Figure 3.9: Computer generated live segment coordinates, using C3D collection software, with; a) electromagnetic source box and sensors; stylus plus three receivers, before calibration, b) individual anatomical segments after calibration on a participant, and c) diagrammatic model showing individual segments (arm, forearm, hand), anatomical coordinates for each segment, and xyz orientation for each segment. Description for each anatomical coordinate is provided in table 3.1.

3.6 Data Processing, Analysis, and Peak Wrist Angle Definition

3.6.1 Data Processing and Analysis

The Polhemus data from all testing procedures was processed using Visual 3D v3.79 (C-Motion, Germantown, MD, USA). A static calibration file (c3d File) was originally constructed, defining the three segments; upper arm, forearm, and hand. A model template (mdh file) was then created using Visual 3D software which contained the segments with defined proximal and distal anatomical reference points (Figure 3.9 and Table 3.1). The mdh file was used for subsequent data processing of all participants.

Following a comparable protocol to (Schmitz et al., 2014), marker trajectories were filtered using a low-pass fourth order zero-lag Butterworth filter in Visual 3D, using 10 Hz as the cut off frequency. This frequency was defined through visual inspection during pilot testing distinguishing between noise (e.g., glove vibration/movement) and true measurements during the impact phase. The body-fixed reference frames were then constructed using the marker positions. The filtered trajectories of the digital markers were subsequently used to compute orientation of the distal segment relative to the proximal one using Cardan angles (Grood and Suntay, 1983). Positive and negative rotations around the x-axis were defined as FLEX and EXT respectively (Figure 3.10). Positive and negative rotations around the y-axis were defined as RD and UD respectively (Figure 3.10). For the surrogate and quasi-static testing an event marker was created corresponding to the maximum and minimum points of all four wrist motions; FLEX, EXT, UD, and RD (Figure 3.10).

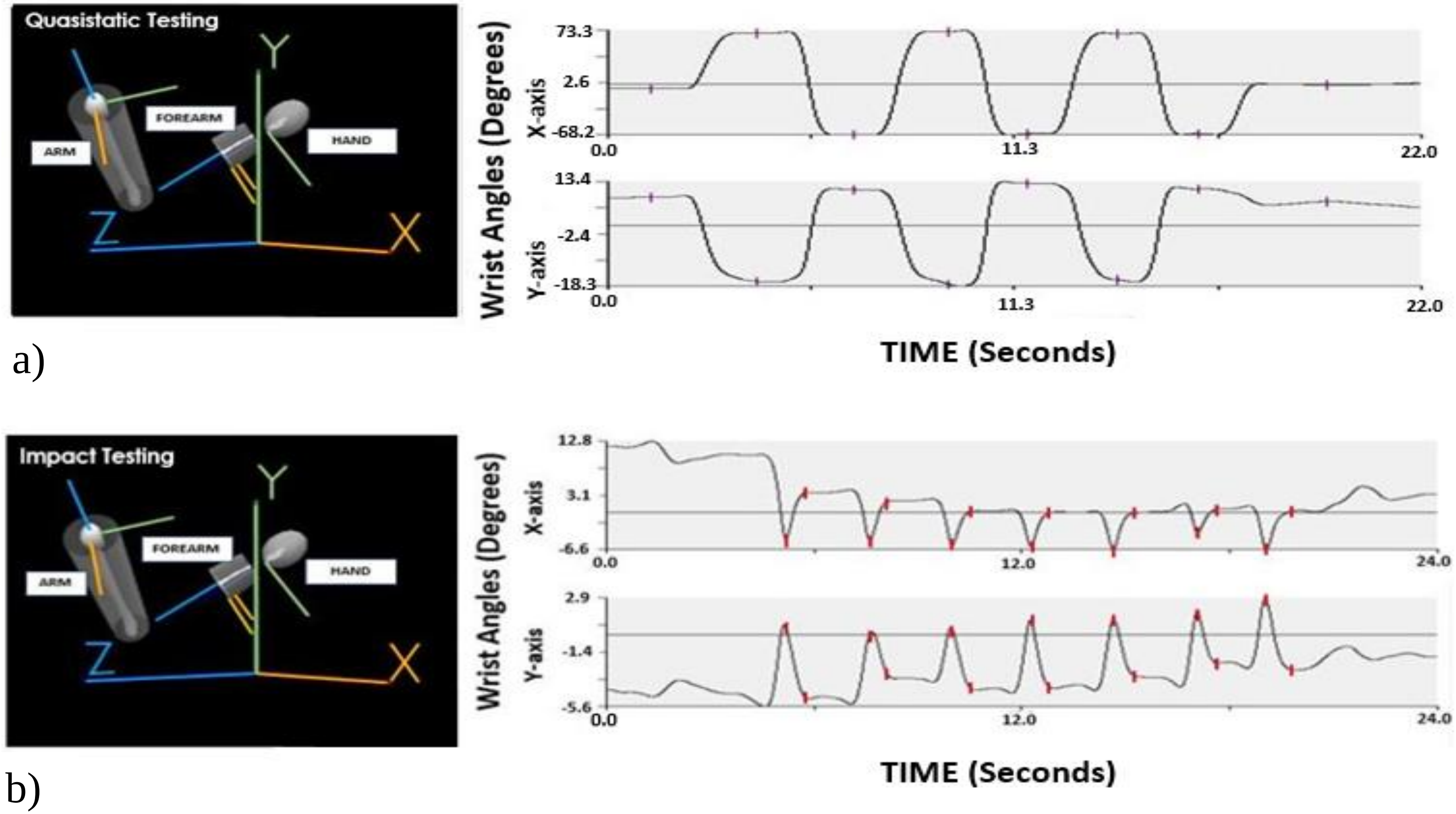


Figure 3.10: Computer generated models for wrist motion for quasistatic and impact testing using Visual 3D Software: On the left, computer generated model showing individual anatomical segments; arm, forearm, hand. On the right, FLEX-EXT (x-axis) and UD-RD (y-axis) wrist angles with event markers (red) created for; **a)** quasistatic testing and **b)** impact testing; Jab shot. *Figure source adapted from Gatt, Allen and Wheat, (2021;2020)*.

3.6.2 Peak Wrist Angle Definition

For the impact testing (Figure 3.10b), the peak wrist angle calculated was defined as the maximal angular displacement occurring on impact. The wrist angle was identified using three combined methods; i) visual observation of the virtual upper limb (tested at 240 Hz) to identify the point of hand impact observed at terminal elbow EXT combined with terminal shoulder FLEX, ii) movement at the x-axis and y-axis aligned together with displacement observed to occur simultaneously at the perceived point of hand impact, and iii) movement at the x-axis aligned with acceleration of the wrist with the maximum acceleration observed to occur simultaneously with maximum x-axis displacement. While the markers at the arm for the participants were not directly required for wrist measurements, these were used to assist visual observation of the virtual upper limb in identifying the wrist angle at impact. For punch testing, an event marker was created corresponding to the maximum and minimum points of all four wrist motions occurring on impact with the bag; FLEX, EXT, UD, RD (Figure 3.10).

3.7 Chapter Conclusion

The process of identifying an appropriate methodology for data collection, conversion, processing, and analysis was provided throughout this chapter. This chapter captured common methodologies amongst the studies conducted in Chapters 4 to 6. The main aim was to ensure processes were viable, especially pertaining to the software used, by allowing for a systematic approach. Although the methodology was identified as suitable to measure wrist motion on impact in boxing, accuracy and repeatability of this method is yet to be assessed to ensure this system is a valid tool. The next chapter will therefore consider the validity of this method, ensuring it meets the requirements for subsequent studies.

4.0 Assessing the Accuracy and Repeatability of Wrist Joint Angles in Boxing using an Electromagnetic Tracking System

4.1 Introduction

As mentioned, studies investigating the kinematics of boxing have provided information on the range of motion occurring at the shoulder and elbow joints, but not the wrist (Piorkowski, Lees and Barton, 2011; Whiting, Gregor, and Finerman, 1988). These studies, however, used reflective surface markers, placed directly on the skin, and camera-based motion capture system. Placing markers on the skin is not feasible in boxing, as bandages and gloves cover the hand-wrist.

In Chapter 2, a comparison of different equipment was considered with a rationale provided for selecting a wired electromagnetic tracking system. This choice was supported in Chapter 3 with trial and refining of the methodology. The aim of this chapter was to investigate the accuracy and repeatability of an electromagnetic tracking system in measuring wrist motion during punching in boxing. This study, (Gatt, Allen and Wheat, 2020), included three components; a) a mechanical surrogate-based investigation, using a polyamide hand and forearm shape surrogate, b) an *in-vivo* quasi-static measurement of the wrist, and c) an *in-vivo* measurement of the wrist during boxing punching activities.

4.2 Method

The electromagnetic tracking system described in Chapter 3 was used. Two and three receivers, respectively, were fixed to the surrogate and participants of this study as described in Section 3.2. Segment coordinate systems were defined for both surrogate and participants as described before (Section 3.2).

4.2.1 Surrogate Testing

Multiple positions of wrist angle were determined during three testing sessions; one to assess accuracy and another two for test-retest reliability. Three self-adhesive coloured markers (6 mm diameter) were attached on the surrogate (Figure 3.2), to enable wrist angles of FLEX-EXT to be obtained from the video footage. The surrogate hand was initially placed at an angle of -90° of EXT and moved to a predetermined angle, where it was then held for approximately five seconds using wooden blocks (L: 10 cm x W: 9 cm x H: 4 cm) positioned over the wooden rig (Figure 3.4b). The surrogate hand was then returned to the initial position of -90 degrees. This procedure was performed for six wrist angle positions; three in EXT (-27°, -42.5°, -51°) and three in FLEX (14.5°, 28°, 42°). It is suggested that repeatability or reliability of an instrument and procedures is determined when the measurement tests are separated by short time intervals, also defined as a *test-retest* study design (Gajdosik and Bohannon, 1987). To measure test-retest reliability the system was recalibrated, the same six wrist angle positions performed, and data collected again. This re-test procedure was repeated one more time. Wrist angles were recorded at a resolution of 60 fps using a digital camcorder (Panasonic HC-V550), positioned with the image plane parallel to the plane of motion of the surrogate hand, from a distance of 150 cm. Three self-adhesive coloured markers (6 mm diameter) positioned on the side of the surrogate were digitised in the video footage (Kinovea, open licence 0.8.15) to calculate wrist angle.

4.2.2 In-Vivo Testing

4.2.2.1 Participants

To be included in the study, boxers met the criteria described in Chapter 3. To determine sample size, a priori power analysis was conducted using GPower 3.1.9.4 with a large effect size (p H1) set at 0.5 (Cohen, 1988), power (1 - β) set at 0.80 and α = 0.05, two-tailed. This analysis showed a sample size of N = 29. Selected participants were 29 GB Boxers forming part of the National Olympic Squad (23 men and 6 women). Characteristics (mean ± standard deviation) were as follows: age 24 ± 4 years (range: 19–34 years), stature 178 ± 10 cm (range: 160–198 cm), and mass 71 ± 17 kg (range: 50–114 kg). The study protocols were approved by local Research Ethics Committee (Ref No HWB-SandE-42).

4.2.2.2 Quasistatic Testing

The forearm was placed on the same rig used for the surrogate testing. Similar to the surrogate testing, wrist angular position was recorded at a resolution of 60 fps using the digital camcorder positioned at a distance of 150 cm, with the image plane parallel to the plane of wrist motion. Three self-adhesive coloured markers (6 mm diameter) were attached (Figure 4.1), to enable wrist angles of FLEX-EXT to be obtained from the video footage, on bone landmarks; lateral placement over Triquetrum, tip of 5th MC, and lateral epicondyle (Abd El-Raheem, Kamel, and Ali, 2015). For UD-RD three similar markers were also used, with the forearm positioned in mid-pronation, on bone landmarks; dorsal Capitate, 3rd MC, dorsal midline of the forearm (Abd El-Raheem, Kamel, and Ali, 2015).

All motions; FLEX, EXT, UD, and RD, were performed three times followed the procedures described before (Section 3.4.2.2). A frame was collected at the static angle which the wrist was held at for each motion, extracted from the video recording, and analysed using the Kinovea software program (Figure 4.1). The wrist angles obtained were used for further statistical analysis. Similar to the surrogate testing, to measure test-retest reliability for FLEX-EXT the system was recalibrated, and the data collected again. This procedure was equally performed for measuring UD-RD.

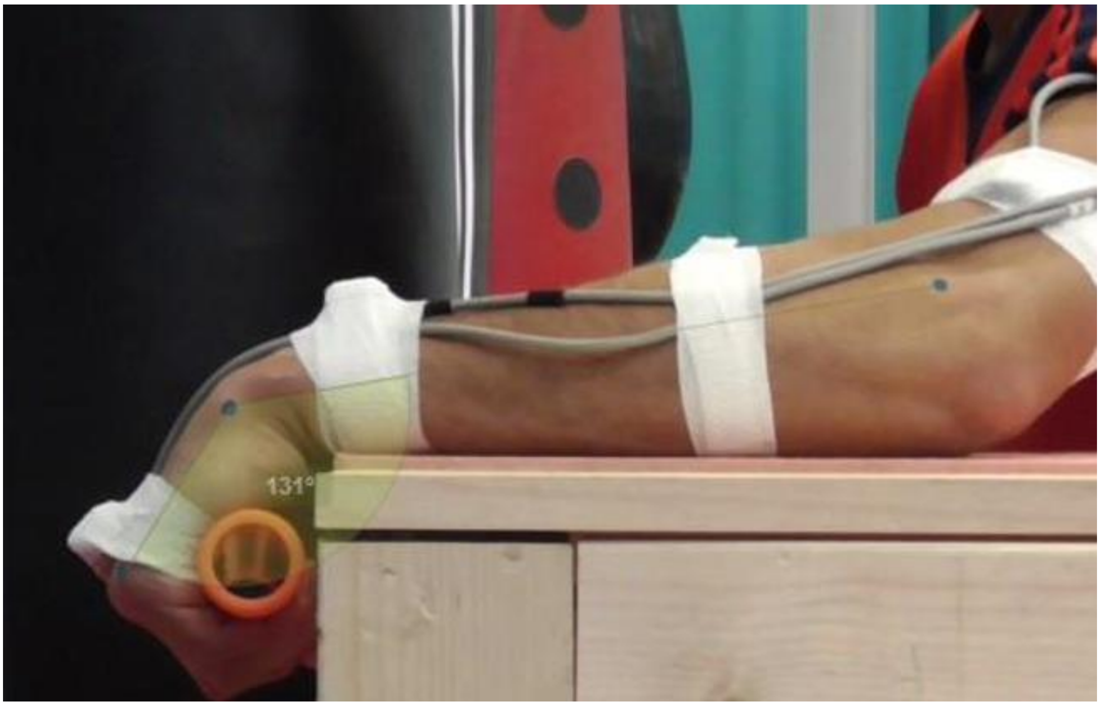


Figure 4.1: Quasistatic data capturing using a camera motion-based system. Kinovea software analysis showing an example of quasi-static testing for FLEX. Three self-adhesive markers (blue) can be observed; at the hand, wrist, and elbow. *Figure source from Gatt, Allen and Wheat (2020).*

4.2.2.3 Impact Testing

Impact testing, to quantify wrist motion on impact, was performed using the same equipment as described before (Section 3.4.2.3). Each participant was then asked to throw six shots on a boxing bag, for both Jab and Hook shots, using the same procedures described before (Section 3.4.2.3). The 2nd to 5th shots were used for statistical analysis, calculating the mean of trial peak (Chapter 3).

4.2.3 Data Processing, Analysis, and Peak Wrist Angle Definition

The electromagnetic tracking system data from all testing procedures was processed and analysed using the methods described before (Section 3.6). Peak wrist angle on impact with the bag was identified using a previously defined manual method (Section 3.6).

4.3 Statistical Analyses

Data was analysed using Excel 2019 and Jamovi (Version 1.0.0.). Z-Scores for skewness and kurtosis were used to test for normal distribution of data with the threshold for the observed values set at ±2 standard deviation of the predicted values (Appendices).

Pearson Coefficient Correlation (r) was used to assess the relationship between the electromagnetic tracking and video-based systems. To assess how closely the means of both systems compared with each other a paired t-test (two-tailed) was used. To assess the agreement of the electromagnetic tracking system with the video-based system in the quasistatic testing, Bland-Altman analysis was performed for each of the four motions tested; FLEX, EXT, UD, and RD. When comparing a gold-standard measurement (fluoroscopic verification) of wrist motion, with three commonly used manual goniometric alignment techniques in clinical settings, a difference of up to 7° was observed for all techniques (Carter et al., 2009). No difference was observed between the techniques. Walmsley et al. (2018) suggested that for equipment used to have adequate accuracy, in measuring upper limb motion, it should have an error of <5°. In this systematic review, the authors used the following parameters to guide their interpretation of measurement error; <2° considered acceptable, between 2° to 5° regarded as reasonable but may require consideration when interpreting data, and > 5° of error interpreted with caution. However, these parameters where derived from lower limb motion analysis, with the authors acknowledging that in comparison upper limb motion, lower limb motions are less complex (Walmsley et al., 2018). Walmsley et al. (2018) observed that when comparing wearable sensors to customised software, using a robotic device, a threshold of 3.9° was observed for replica/simulated movements at the wrist for FLEX/EXT. In the same systematic review, when comparing a pseudo-gold standard (three-dimensional optical motion analysis) to wearable sensors, with in-vivo participants, differences exceeded the 5° threshold, with up to 15 degrees differences. The authors did suggest that <5° were achievable with a high level of customisation, however, accepting that errors >5° in clinical settings will occur. In another study comparing marker-based kinematic assessment of hand-wrist motion with manual goniometric measurements, mean differences between both techniques of 4° and 5.2° were observed respectively for UD-RD and FLEX-EXT motions (Cook et al., 2007).

Based on these studies, a threshold difference between the electromagnetic tracking system and video-based for wrist motions for the surrogate was considered acceptable at <4.0°. For in-vivo assessment a mean difference of <6° were considered acceptable, 6° to 7° were considered reasonable but may require consideration, >7° error interpreted with caution. Further the upper limits of agreement were set to 15°.

Intra-participant reliability of each measure for all tests performed (i.e., surrogate, quasi-static, and impact) was examined using a two-way mixed-effects model with absolute agreement intraclass correlation coefficient (ICC) (Koo and Li, 2016). The following benchmarks for ICC for reliability were used: *Poor* (0.00–0.20), *Fair* (0.21–0.40), *Moderate* (0.41–0.60), *Substantial* (0.61–0.80), and *Good* (0.81–1.00) agreement (Landis and Koch, 1977).

4.4 Results

A high correlation was observed (Table 4.1) between the wrist angles recorded from the electromagnetic and video-based systems. Paired samples t-test (two-tailed) comparing mean differences for each motion for the electromagnetic with the video-based systems were non-significant ($p>0.05$) (Table 4.1). The electromagnetic tracking system showed acceptable agreement with the video-based system, for estimating FLEX-EXT (0.04° to 0.20° limits of agreement) for the surrogate testing using the parameters set of <3.9° (Table 4.2). For the in-vivo quasistatic testing, acceptable agreement with the video-based system at estimating UD-RD (<4° mean difference) and FLEX-EXT motions (<6° mean difference) was observed using the parameters set of a mean of <6° (Table 4.2). Further the limits of agreement ranging from 0.4° to 11.1° (Table 4.2 and Figure 4.2) met the Bland-Altman parameters set with a threshold of up to 15°, which means the model can be used when the acceptable difference from the marker-based video analysis is within this range. In all the motions, homoscedasticity was observed between the residual (i.e., observed) and the predicted mean angles (Figure 4.2).

Table 4.1: Agreement of the electromagnetic tracking system with the video system for the surrogate and quasi-static testing using Pearson Correlation Coefficient and Paired T-Test (2-Tailed). Descriptive statistics presented (units in degrees). *Amended from Gatt, Allen and Wheat (2020).*

	Motion	Correlation	Sig	Mean Difference	Standard Deviation	Paired T-Test (2-Tailed)
Surrogate	FLEX-EXT	1	<0.001	0.12	0.08	0.99
Quasi-static	FLEX	0.973	<0.001	5.73	2.73	0.07
	EXT	0.998	<0.001	2.46	0.83	0.49
	UD	0.986	<0.001	3.52	1.62	0.15
	RD	0.989	<0.001	2.15	0.93	0.2

Table 4.2: Agreement of the electromagnetic tracking system with the video system for the surrogate and quasi-static testing using Bland-Altman analysis (units in degrees).

	Motion	Mean Difference	Lower Limit of Agreement	Upper Limit of Agreement
Surrogate	FLEX-EXT	0.12	0.04	0.20
Quasi-static	FLEX	5.73	0.38	11.08
	EXT	2.46	0.83	4.09
	UD	3.52	0.36	6.67
	RD	2.15	0.33	3.97

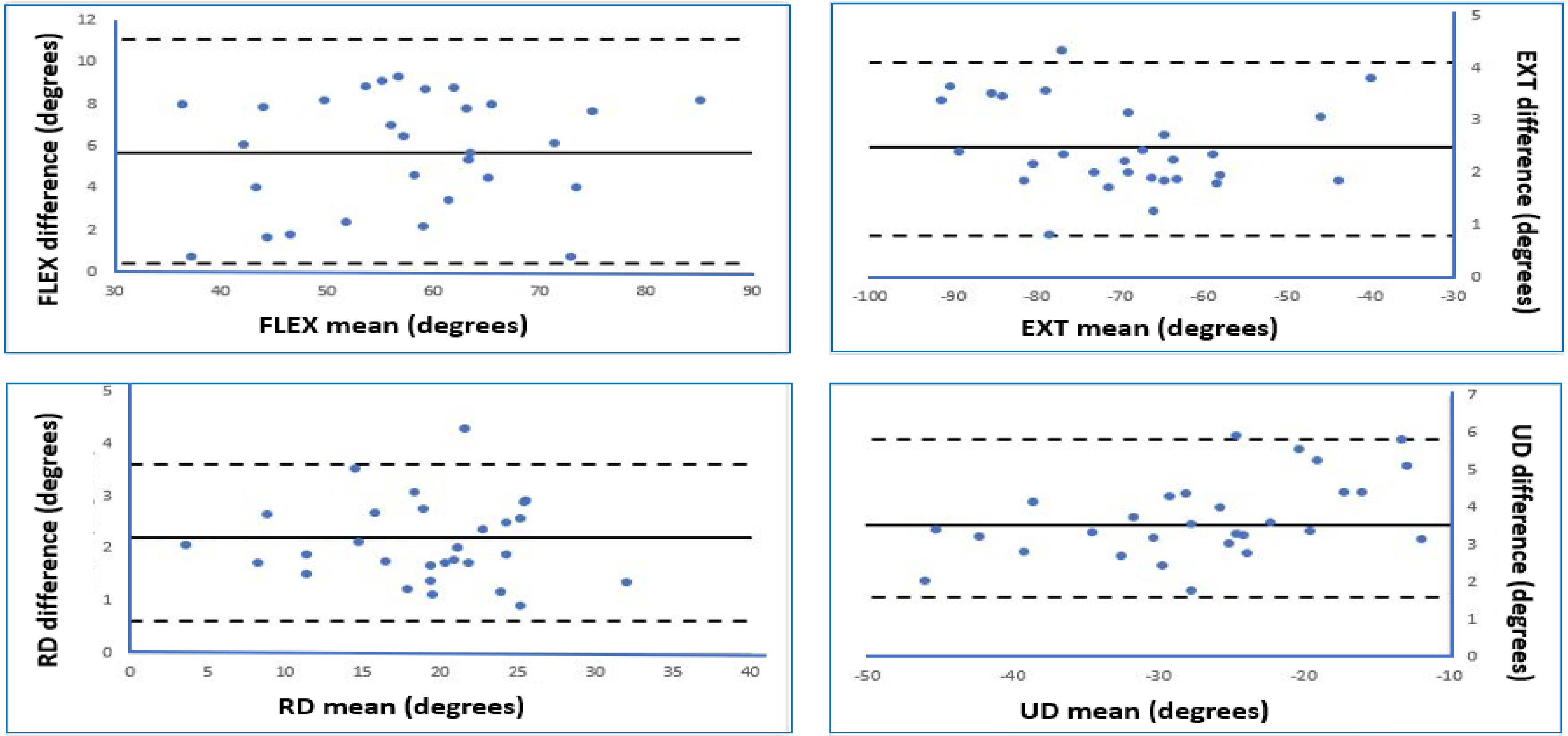


Figure 4.2: Bland-Altman analysis for the quasi-static testing. All units in degrees. *Figure source from Gatt, Allen and Wheat (2020).*

The electromagnetic tracking system demonstrated good reliability (ICCs > 0.9) (Landi and Koch, 1977), for both the surrogate and quasistatic data (Table 4.3). Jab and Hook shots for wrist motions occurring during the impact testing in FLEX-EXT yielded good reliability (ICCs > 0.8), whilst a substantial reliability (ICCs > 0.6) (Landis and Koch, 1977), for both types of shots for wrist motions was recorded in UD-RD (Table 4.4).

Table 4.3: Reliability for wrist motion during quasistatic testing with means, intraclass correlation coefficient (ICC), and 95% Confidence Intervals (CI) of wrist motion capture systems. All units in degrees. *Table source from Gatt, Allen and Wheat (2020).*

	Motion	**1st**	**2nd**	**3rd**	**ICC**	**95% CI (%)**
Surrogate (Video System)	FLEX-EXT				1	0.999-1.000
Surrogate (Electromagnetic Tracking System)	FLEX-EXT				1	0.999-1.000
Quasi-static (Video System)	FLEX	58.3 ± 11.9	59.1 ± 12.1	59.2 ± 12.0	0.976	0.957-0.988
	EXT	69.5 ± 13.0	69.1 ± 13.7	69.3 ± 13.2	0.987	0.975-0.973
	UD	26.1 ± 9.4	26.6 ± 9.6	26.5 ± 9.5	0.967	0.941-0.983
	RD	19.0 ± 6.3	19.8 ± 6.1	19.9 ± 6.5	0.970	0.946-0.985
Quasi-static Intrasession (Electromagnetic Tracking System)	FLEX	52.6± 11.6	53.3 ± 11.9	53.5 ± 12.0	0.961	0.930-0.980
	EXT	71.7 ± 13.3	71.7 ± 13.8	71.8 ± 13.3	0.990	0.982-0.995
	UD	29.7 ± 8.9	30.0 ± 9.2	30.1 ± 8.7	0.970	0.944-0.985
	RD	17.0 ± 6.1	17.7 ± 6.2	17.6 ± 6.6	0.973	0.951-0.987
Quasi-static Intersession (Electromagnetic Tracking System)	FLEX				0.992	0.983-0.996
	EXT				0.996	0.991-0.998
	UD				0.941	0.879-0.972
	RD				0.974	0.945-0.988

Table 4.4: Reliability for wrist motion during impact testing for the 2-5th Jab and Hook shots with means, Intraclass Correlation Coefficient (ICC), and 95% Confidence Intervals (CI). All units in degrees. *Table source from Gatt, Allen and Wheat (2020).*

Shot	Motion	2ND	3RD	4TH	5TH	ICC	95 CI (%)
JAB	FLEX-EXT	7.5 ± 4.3	7.9 ± 4.6	7.8 ± 5.2	7.2 ± 4.7	0.850	0.757-0.918
JAB	UD-RD	3.0 ± 1.8	2.8 ± 1.8	2.9 ± 2.1	2.4 ± 2.1	0.679	0.522-0.813
HOOK	FLEX-EXT	4.8 ± 2.7	4.3 ± 2.7	5.0 ± 3.7	4.8 ± 3.2	0.805	0.692-0.892
HOOK	UD-RD	2.1 ± 1.8	1.9 ± 2.0	1.7 ± 1.5	1.8 ± 1.4	0.700	0.549-0.827

4.5 Discussion

When testing a rigid surrogate wrist held at different angles, which eliminates potential errors of anatomy and skin movement, joint angles measured with the electromagnetic tracking system agreed with the video-based system within 0.2°. For the quasi-static measurement of boxers' wrists, the electromagnetic tracking system agreed with the marker-based video system within 2° to 6° for all four movements tested, with the largest mean difference of 5.7° similar to reported mean differences of 5° to 6° observed in other clinical studies (Butler et al., 2011; Noehren et al., 2012).

Agreement between the electromagnetic tracking system and video-based systems in the quasistatic testing was further confirmed with Bland-Altman analysis (Bland and Altman, 2003; Field, 2014). The largest difference (11.1°) between the two systems was observed to occur during FLEX testing. Arman et al. (2021) assessed the agreement between two systems to measure wrist ROM, an optic tracking system compared with a universal goniometer. It was found that the mean difference between the two measurement methods was low (less than 5°) for almost all ROMs. In this study, the limits of agreement observed were up to 15°. The authors concluding that the optic tracking system was a valid tool to measuring wrist ROM (Aramn et al., 2021). Similarly in the current study, the mean difference between the two systems was less than 5° for all motions except wrist FLEX recorded at 5.7°. The upper limits of agreement were within 6.7° for all motions, except for FLEX. The electromagnetic receivers were placed on the dorsum of the hand, whilst the self-adhesive markers for video capturing were placed on the medial aspect, therefore providing an explanation for the larger difference obtained during FLEX compared with the other motions. Considering that the hand was maintained in a fist position, it was expected that the overlying structures (skin and underlying fascia) on the dorsum of the fingers, hand and wrist would be more stretched when compared to the volar, medial, and lateral aspects. The bandage, used for the impact testing, would have potentially reduced movement of the electromagnetic receivers on the underlying skin due to direct pressure onto these receivers. The use of the bandage during the quasi-static method, however, was not viable due to the requirement of the self-adhesive markers to be placed on the skin and captured with the video camera. Securing the receivers during the impact testing was important, and therefore considered when bandaging the hand-wrist complex.

Another consideration is that substantial inter-carpal joint movements occur in the region of the wrist (de Lange, Kauer, and Huiskes, 1985; Gellman et al., 1988; Sun et al., 2000). Several authors have stated that the centre of rotation for the wrist occurs at the Capitate bone (Andrews and Youm, 1979; Brumbaugh et al., 1982; Jackson, Hefzy, and Guo, 1994). In a study using high speed video data acquisition for three-dimensional range of movement analysis of a cadaveric wrist, it was observed that during wrist FLEX-EXT, the instantaneous screw axis was found to qualitatively pass through the head of the Capitate however, it was not limited or fixed to the Capitate (Patterson et al., 1998). Patterson et al (1988) maintain that centre of rotation calculations assume planar motion and do not account for slippage between the carpal bones during normal carpal motion. To potentially provide a better comparison, a four-point video analysis could be considered based on the understanding that the wrist is more complicated and modelling it as a fixed hinge joint might not be anatomically correct. In the current study, the electromagnetic tracking system agreed with a three-point video analysis system, with the axis of rotation considered at the Capitate. While care was taken in positioning the camera, the two-dimensional video analysis could present a potential source of error due to cross talk between FLEX-EXT and UD-RD resulting in some out of plane motion. Future work could consider using three-dimensional analysis techniques, such as stereo calibrated cameras or a commercial marker-based motion capture system.

During wrist motion, the radio-lunate joint contributes more motion in FLEX than the Capito-Lunate joint, with the opposite occurring in EXT (Patterson et al., 1998). These underlying biomechanical differences, combined with potential skin movement, can easily contribute to variations with repeated movements. In the current study, intra-rater reliability of the video analysis approach was evaluated by measurement of the wrist joint ROM. The ICC for all four motions was in a range of 0.967-0.976 indicating good reliability [(ICCs >0.9) (Landis and Koch, 1977), comparable to another study using a similar methodology (Gajdosik and Bohannon, 1987).

Assessing the accuracy of the electromagnetic tracking system during impact testing was not possible, the information from the surrogate and quasi-static testing was therefore considered. For repeatability of the electromagnetic tracking system during impact testing, reliability of two commonly used shots in boxing (Jab and Hook) was performed. For both types of shots, FLEX-EXT yielded better reliability (ICC range; 0.805-0.850) than UD-RD (ICC range; 0.679-0.700)**.** The difference in reliability between FLEX-EXT and UD-RD potentially contributed to errors with the two-dimensional video analysis setup. Compared to gait analysis in the lower limb, motion analysis of the upper limb carries several disadvantages. Mainly that there is no single relevant functional activity for the upper limb, and that functional activities in this region show a larger variation of execution in the general population as opposed to gait patterns (van Andel et al., 2008). Boxing is not considered an activity of daily living and therefore not an area that is widely understood and researched. In boxing, the objective is to restrict movement at the wrist to improve transference of forces occurring from the lower limb and trunk towards the upper limb, and into the opponent. This movement restriction at the wrist is also important to decrease injuries occurring to the boxer, evident from the common practice of wrapping hands for both training and competition. Conversely, in activities of daily living and other sports, it is often important for motion to occur in the wrist joint. This current study was therefore important in identifying a technology that can measure what level of wrist motion occurs during impact in boxing, whilst still using the wrapping material and gloves required.

4.6 Chapter Conclusion

This chapter describes a new method for quantifying wrist motion in boxing using an electromagnetic tracking system. Surrogate testing procedure utilising a polyamide hand and forearm shape, and *in-vivo* testing procedure utilising 29 elite boxers, were used to assess the accuracy and repeatability of the system. Two-dimensional kinematic analysis was used to calculate wrist angles using photogrammetry, whilst the data from the electromagnetic tracking system was processed with Visual 3D software. The electromagnetic tracking system agreed (paired *t*-test and limits of agreement) with the video-based system in both the surrogate (<0.2°) and quasistatic testing (<6°). Both systems showed a good intraclass coefficient of reliability (ICCs >0.9). In the punch testing, for both repeated Jab and Hook shots, the electromagnetic tracking system showed good reliability (ICCs >0.8) and substantial reliability (ICCs

>0.6) for FLEX-EXT and UD-RD angles respectively. The results indicate that wrist kinematics during punching activities can be measured using an electromagnetic tracking system. This methodology was therefore considered to quantify wrist motion on impact, covered in the following chapter.

5.0 Quantifying Wrist Angular Excursion on Impact for Jab and Hook Lead Arm Shots in Boxing

5.1 Introduction

Hyperflexion of the wrist on impact in boxing is considered an important mechanism of injury towards the CMC joint of the hand (Chapter 2). Considering that this mechanism has been proposed for a long time in boxing (Noble, 1987), it is surprising that wrist motion has not been previously quantified. Possibly this is due to lack of an adequate methodology, which has now been identified in Section 2.7 and Chapter 3, and further investigated for accuracy and reliability in Chapter 4. FLEX in the sagittal plane appears to be the only wrist movement typically considered on impact (Loosemore et al., 2017; Noble, 1987). Kinematic studies, however, describe a biplanar coupled motion occurring naturally in daily activities, described as DTM of the wrist (Garcia-Elias et al., 1995; Ishikawa et al., 1999; Moritomo et al., 2004; Saffar and Semaan, 1994; Wolfe et al., 2006), rather than a uniaxial motion, as discussed in Chapter 2.

While injuries at the hand can occur with both types of commonly used shots in boxing, Jab (straight arm) shots appear to contribute more to CMC injuries than Hook (bent arm) shots. This difference in injuries observed between straight and bent arm shots has been explained through the system of levers (Chapter 2), suggesting more wrist angular motion (i.e., excursion) occurring on impact with straight than bent arm shots.

To understand the possible causes of injuries at the hand in boxing, knowledge of the wrist kinematics during the impact phase of punching is required. In this study (Gatt, Allen and Wheat, 2021), wrist motion was assessed on impact during lead arm straight and bent arm shots. It was hypothesised that; a) ulnoflexion motion occurs in both Jab and Hook shots, b) the amount of wrist angular excursion could be identified on impact for both Jab and Hook shots, and c) more wrist angular excursion on impact occurs in Jab than for Hook shots.

5.2 Method

5.2.1 Participants

To be included in the study, boxers met the criteria described in Chapter 3. To determine sample size, a priori power analysis was conducted using GPower 3.1.9.4 with a medium effect size (d) set at 0.6 (Cohen, 1988), power (1 - β) set at 0.80 and $\alpha = 0.05$, two-tailed. This analysis showed a sample size of $N = 24$. Participants were recruited from both genders, as there were no studies supporting wrist kinematics or injury variations among male and female boxers. Participants (23 male, 6 female) were recruited. Characteristics (mean ± standard deviation) were as follows: age 24 ± 4 years (range: 19–34 years), stature 178 ± 10 cm (range: 160–198 cm), and mass 71 ± 17 kg (range: 50–114 kg). The study protocols were approved by local Research Ethics Committee at Sheffield Hallam University (Ref No HWB-SandE-42).

5.2.2 Experimental Design and Testing Procedures

The electromagnetic tracking system described in Chapter 3 was used. Three receivers were fixed to the upper limb of the participants of this study, with segment coordinate systems defined, as described before (Chapter 3). This study was a repeated measure design (i.e., repeated measurements were made for each experimental unit).

5.2.2.1. Quasistatic Testing

The quasistatic testing allowed wrist motion on impact, during the impact testing, to be quantified as a percentage of both the AROM occurring with bandaging techniques, and TROM occurring with no bandaging. The bandaging technique used the same material and technique described before (Section 3.2.2.2). Similar to a previous study (Chapter 4), all motions; FLEX, EXT, UD, and RD, were performed three times followed the procedures described before (Section 3.4.2.2).

5.2.2.2. Impact Testing

Impact testing, to quantify wrist motion on impact, was performed using the same equipment as described before (Section 3.4.2.3). Each participant was then asked to throw six shots on a boxing bag, for both Jab and Hook shots, using the same procedures described before (Section 3.4.2.3). The 2nd to 5th shots were used for statistical analysis, calculating the mean of trial peak (Chapter 3).

5.2.3 Data Processing, Analysis, and Definitions for Peak Wrist Angle.

The tracking system data from all testing procedures were processed and analysed following a similar protocol (Section 3.6), used in a previous study (Chapter 4). Peak wrist angle on impact with the bag was identified using a previously defined manual method (Gatt, Allen and Wheat, 2020; Section 3.6).

5.3 Statistical Analyses

Z-Scores for skewness and kurtosis were used to test for normal distribution of data with the threshold for the observed values set at ±2 standard deviation of the predicted values (Appendices). Differences between angular excursions of FLEX and UD for Jab or Hook shots, or between different Jab and Hook shots for the same angular excursion of FLEX or UD, were analysed using a paired samples two-tailed *t*-test ($\alpha = 0.05$). Data was analysed using Excel 2021 and Jamovi (Version 1.8.4.). All data are presented as means ± standard deviations. The magnitude of any differences (effect size) was assessed using Cohen's *d* with the following benchmarks; *small* (0.20), *medium* (0.50), *large* (0.8), and *very large* (1.3) (Sullivan and Feinn, 2012).

5.4 Results

All data for Jab and Hook shots were normally distributed with 95% of the observations falling inside the predicted Z-Scores (Appendices). For Jab shots, wrist angular excursions occurred concurrent in FLEX and UD, with a mean of 9.3±2.0° and 4.7±1.2° respectively (Table 5.1). Wrist angular excursions were greater ($t=10.3$, $p<0.001$, $d=1.9$) (Appendices) for FLEX than UD. Wrist angular excursions represented 17.2±4.3% and 18.3±8.0% of the total wrist active ROM (TROM) for FLEX and UD respectively (Table 5.2). All wrist angular excursions on impact were under 30% of TROM. For Hook shots, wrist angular excursions on impact, occurred concurrent in FLEX and UD, with a mean of 5.5±1.1° and 3.3±0.9° respectively (Table 5.2). Wrist angular excursions were greater ($t=8.6$, $p < 0.001$, $d=1.6$) (Appendices) for FLEX than UD. Wrist angular excursions represented 10.4±3.2% and 12.8±6.3% of the TROM for FLEX and UD respectively (Table 5.2). All wrist angular excursions on impact were under 20% of TROM.

Table 5.1: Mean angles and 95% Confidence Intervals for TROM from the quasi-static ROM testing, and wrist angular excursions from the impact testing. *Table source from Gatt, Allen and Wheat (2021).*

	Shot	Motion	ROM (degrees)	95% CI
TROM (Quasistatic Testing)		FLEX	55.3 ± 11.2	59.5-51.0
		EXT	70.1 ± 14.0	75.4.3-64.7
		UD	28.8 ± 9.4	32.3-25.2
		RD	18.8 ± 6.8	21.3.-16.2
Wrist Angular Excursions (Impact Testing)	JAB	FLEX	9.3 ± 2.0	8.6-10.1
	JAB	UD	4.7 ± 1.2	4.2-5.2
	HOOK	FLEX	5.5 ± 1.1	5.1-5.9
	HOOK	UD	3.3 ± 0.9	2.9-3.6

Table 5.2: Mean angles and 95% Confidence Intervals for percentage wrist angular excursions. Wrist angular excursions on impact are expressed as a percentage of TROM. *Table source from Gatt, Allen and Wheat (2021).*

	Shot	Motion	ROM (%)	95% CI
% Wrist Angular Excursions on Impact (Wrist angular excursions on impact expressed as a % of TROM)	JAB	FLEX	17.4 ± 4.3	15.7-19.0
	JAB	UD	18.3 ± 8.0	15.3-21.4
	HOOK	FLEX	10.4 ± 3.2	9.2-11.6
	HOOK	UD	12.8 ± 6.3	10.4-15.2

When comparing Jab and Hook shots, wrist angular excursions on impact were greater in both FLEX (t=9.0, p<0.001, d=1.7) and UD (t=8.4, p<0.001, d=1.6) for Jab than Hook shots (Appendices). When expressed as a percentage of TROM, wrist angular excursions were also greater in both FLEX (t=6.9, p<0.001, d=1.3) and UD (t=4.9, p<0.001, d= 0.9) for Jab than Hook shots (Appendices).

5.5 Discussion on Wrist Angular Motion on Impact for Both Shot Types.

This study quantified wrist angular motion in boxing, whereas others investigated the kinematics occurring at more proximal joints to the wrist in this sport (Bergün, et al., 2018; Cheraghi et al., 2014; Dinu and Louis, 2020; Fisk, 1980; Noble, 1987; Piorkowski, Lees and Barton, 2011; Saffar and Semaan, 1994; Stanley et al., 2018; Sweeney et al., 2012; Whiting, Gregor and Finerman, 1988). The current study recruited elite boxers and used an electromagnetic tracking system, which was previously found to be accurate and reliable for both Jab and Hook shots (Chapter 4). The results identified ulnoflexion motion occurring in both Jab and Hook shots. All wrist angular excursions on impact occurred within 30% of the TROM, quantified using a quasistatic active ROM method (Chapter 3), before impact testing. Further, greater wrist angular excursions on impact occurred in Jab than Hook shots.

5.5.1 Type of Wrist Motion

To date, FLEX is the only wrist motion proposed on impact in boxing (Loosemore et al., 2017; Noble, 1987), with no study quantifying what type of wrist motion is occurring. In this current study, UD occurred concurrent with FLEX for both Jab and Hook shots. This agrees with other kinematic studies indicating that the DTM of the wrist occurs in activities of daily living and other sports (Fisk, 1980; Li et al., 2005;

Moritomo et al., 2004; Palmer et al., 1985; Sweeney et al., 2012). The ECRL and ECRB muscles have been observed to perform eccentric and isometric contraction respectively during repetitive movements like pushing and turning a spring-loaded mechanism (Murgia et al, 2011), suggesting that on impact these muscles would function to limit the amount of ulnoflexion angular excursion. Further, these muscles are MiC supinators (Salva-Coll et al., 2011). Since the moment induced on impact would be ulnoflexion, ECRL and ECRB would act to stabilise the wrist by inducing a radioextension torque to the wrist and therefore counteracting its natural tendency towards rotating into both FLEX and UD (Salva-Coll et al., 2011).

Boxers are instructed to make a fist before impact, which appears important as co-contraction of the muscles acting at the wrist is required to create stability at this joint (Salva-Coll et al., 2011). Further, maximal grip strength in normal healthy individuals has been observed to occur at 30 to 35° of wrist extension, with a substantial reduction in grip strength when deviation falls outside this range (Lee and Sechachalam, 2016; Murgia et al., 2011; O'Driscoll et al., 1992). Since wrist EXT is predominantly performed by the actions of ECRL and ECRB, it appears that limiting ulnoflexion could influence grip strength and therefore wrist stability on impact in boxing.

5.5.2 Amount of Wrist Motion

Before this study, no information was available on the amount of wrist angular excursion on impact in boxing. For both Jab and Hook shots respectively, FLEX was observed with a mean of 9.3±2.0° and 5.5±1.1°, whilst UD was observed with a mean of 4.7±1.2° and 3.3±0.9°. This represented under 30 and 20% of the TROM for Jab and Hook shots, respectively. Conversely, in other sports like basketball and golf, where the wrist is not ‘forced’ to bend by an opposing target, FLEX has been observed with over 60° of TROM (Ohnishi et al., 1992; Sweeney et al., 2012), indicating over 70% of TROM (Alford, 2021; Kim et al., 2014; Ryu et al., 1991).

In snowboarding (Greenwald, Simpson and Michel, 2013) and skateboarding (Giddins and Giddins, 2021), near terminal wrist EXT angular excursions have been recorded on impact during non-injurious falls. In these sports, the intention is to remain upright rather than impact through the wrist, which occurs as a protective mechanism when attempting to break a fall. The high wrist EXT in snowboarding and skateboarding, therefore, indicates movements are forced from the weight of the body over an open hand planted onto the ground. In the boxing, the wrist is also forced from the weight of the body over the fist, planted onto the target. Conversely, to snowboarding and skateboarding, in boxing the aim is to impact repetitively onto a target, using a ‘controlled’ wrist, with a closed fist. A controlled or stable wrist is therefore required on impact in boxing. A stable wrist has been defined as one which, when loaded within a physiological range, does not deviate from a state of equilibrium at any point within the available ROM (Zdravkovic, Jacob and Sennwald, 1995). In the current study, this state of equilibrium appeared to be under 30% of TROM for both shot types.

5.5.3 Difference in Wrist Motion

Wrist angular excursions on impact were greater in both FLEX and UD for Jab than Hook shots. Hook shots have, however, been observed to have higher fist velocities than Jab shots (Piorkowski, Lees and Barton, 2011; Stanley et al., 2018; Whiting, Gregor and Finerman, 1988). As mentioned in Chapter 2, greater motion occurs at the shoulder than the elbow joint (Cheraghi et al., 2014; Dinu and Louis, 2020;

Piorkowski, Lees and Barton, 2011; Stanley et al., 2018; Whiting, Gregor and Finerman, 1988), and that Hook shots also have a longer trajectory over which to accelerate (Piorkowski, Lees and Barton, 2011). With both higher velocity and impact forces in Hook shots (Lenetsky, Harris, and Brughelli, 2013), greater wrist movement could be expected to occur with Hook than Jab shots. As mentioned in Chapter 2, Jab shots however exhibit a proximal-to-distal sequence. During Jab shots, the elbow joint straightens (extends) rapidly after the punching arm has begun accelerating toward the target, via angular velocities generated at the shoulder joint (Cheraghi et al., 2014; Jessop and Pain, 2016). Conversely, during Hook shots, the elbow is fixed to an approximate right angle whilst the shoulder exhibits a rapid combination of movements (Piorkowski, Lees and Barton, 2011; Whiting, Gregor, and Finerman, 1988). The current study demonstrates that more wrist angular excursion occurs during Jab shots, which are long levers and where the proximal joint (elbow) is mobile, compared to Hook shots which are shorter levers and where the elbow joint is maintained in a more stable position.

5.5.4 Limitations

There are some methodological aspects that should be addressed. The sequence of shots thrown by the participants; Jabs followed by Hooks. Randomisation of shots could have been considered, rather than a pre-selected sequence. Interestingly however, more wrist motion occurred with the first type of shots thrown, Jabs, compared to Hooks, which eliminates the rationale of increased motion linked to potential fatigue. With the known low number of shots thrown, fatigue was not considered. Considering elite boxers are conditioned to throw high volume of shots in any training session, six shots for each shot type would not induce fatigue. However, the methodology was addressed in the following study (Chapter 6), by randomising the order of shots thrown.

Speed of movement of the lead arm was not assessed. Greater wrist angular excursion occurring during Jab than Hook shots could have been due to differences in velocities, rather than lever systems (Chapter 2). Hook shots, however, have shown higher velocities and impact forces than Jab shots (Lenetsky, Harris and Brughelli, 2013; Piorkowski, Lees and Barton, 2011; Stanley et al., 2018; Whiting, Gregor and Finerman,1988). Speed of movement was addressed in the following study (Chapter 6), by calculating average speed of the shots. Further limitations, which apply to both studies, conducted in Chapters 5 and 6, will be discussed in Chapter 7.

5.6 Chapter Conclusion

This study demonstrates the novel and quantifiable effects of wrist kinematics on impact when throwing Jab and Hook shots on a commonly used type of training equipment. On impact both FLEX and UD occur, with more pronounced motion occurring with Jab than Hook shots. This study provides useful information on wrist kinematics during the impact phase of punching and potentially an improved understanding of injury mechanisms in boxing, especially for CMC injuries. Further research, however, is warranted to identify strategies that can influence the kinematics of the wrist on impact in boxing. It is therefore important to consider whether adding rigid tape influences wrist motion in this sport. The effect of taping, and shot type, on wrist motion on impact will be covered in the next chapter.

6.0 Effects of using Rigid Tape with Bandaging Techniques on Wrist Joint Motion during Boxing Shots in Elite Male Athletes

6.1 Introduction

Bandaging techniques, to protect the hand-wrist from injuries, have evolved with differences observed between amateur and professional styles of boxing during competition. (International Boxing Association, 2022; British Boxing Board of Control, 2021; Gems, 2014). As mentioned in Chapter 2, in the professional style of boxing, rigid tape is allowed with no restriction except that the hand must fit in the glove. In the amateur style, at elite international level, a similar technique to the professional style of boxing using rigid tape is allowed in some competition formats. However, rigid tape is not allowed for all competition formats. Some competition formats only allow for bandaging only, using cotton material, which likely offers less support to the wrist. Although the effects of rigid tape on wrist motion in boxing have not been quantified, rigid tape has been used widely in sports as prophylaxis or post-injury management aiming to improve support and stability at joints (Kim et al., 2020; Purcell et al., 2009; Sato et al., 2019).

To date, only one study assessed wrist motion on impact in boxing (Chapter 5). Although standard bandaging was applied the effect of technique was not considered. FLEX occurs concurrently (achieving peak angle on impact at the same time) with UD for both straight and bent arm shots, with both motions greater in straight than bent arm shots (Chapter 5). It was therefore hypothesised that; a) less wrist angular motion on impact occurs with tape added to a traditional bandage technique for both straight

(Jab) and bent arm (Hook) shots, and b) more wrist motion on impact occurs in straight than bent arm shots for both bandage only and bandage plus tape. Further, it was considered opportune to identify; i) if time to peak angle on impact is altered when adding tape, and ii) the effect of taping on reducing wrist motion during quasi-static testing, allowing for a comparison of wrist motion during the impact testing, whilst providing a reference of TROM without any bandaging.

6.2 Method

6.2.1 Participants

To be included in the study, boxers met the criteria described in Chapter 3. To determine sample size, a priori power analysis was conducted using GPower 3.1.9.4 with an effect size (f) set at 0.4 (calculated using a large effect size of $\eta^2 = 0.14$) (Lakens, 2013), power ($1 - \beta$) set at 0.80 and $\alpha = 0.05$, two-tailed. This analysis showed us a sample size of N = 16. Participants, 18 elite male boxers, were recruited. Characteristics (mean ± standard deviation) were as follows: age 23 ± 2 years (range: 19–27 years), stature 177 ± 11 cm (range: 156–195 cm), and mass 71 ± 17 kg (range: 50–114 kg).

6.2.2 Experimental Design and Testing Procedures

The electromagnetic tracking system described in Chapter 3 was used. Similar to previous studies (Chapters 4 and 5), three receivers were fixed to the upper limb of the participants of this study, with segment coordinate systems defined, as described before (Chapter 3).

6.2.2.1. Quasistatic Testing

Similar to a previous study (Chapter 5), the quasistatic testing allowed wrist motion on impact, during the impact testing, to be quantified as a percentage of both the AROM occurring with bandaging techniques, and TROM occurring with no bandaging. In this study, two bandaging techniques were used for both impact and quasistatic testing. Bandage only; a standard bandaging technique (Section 3.4.2.2). Bandage plus tape; a standardised technique (Figure 6.1) using 2.5 cm width rigid (zinc oxide) tape, added to the bandage only technique.

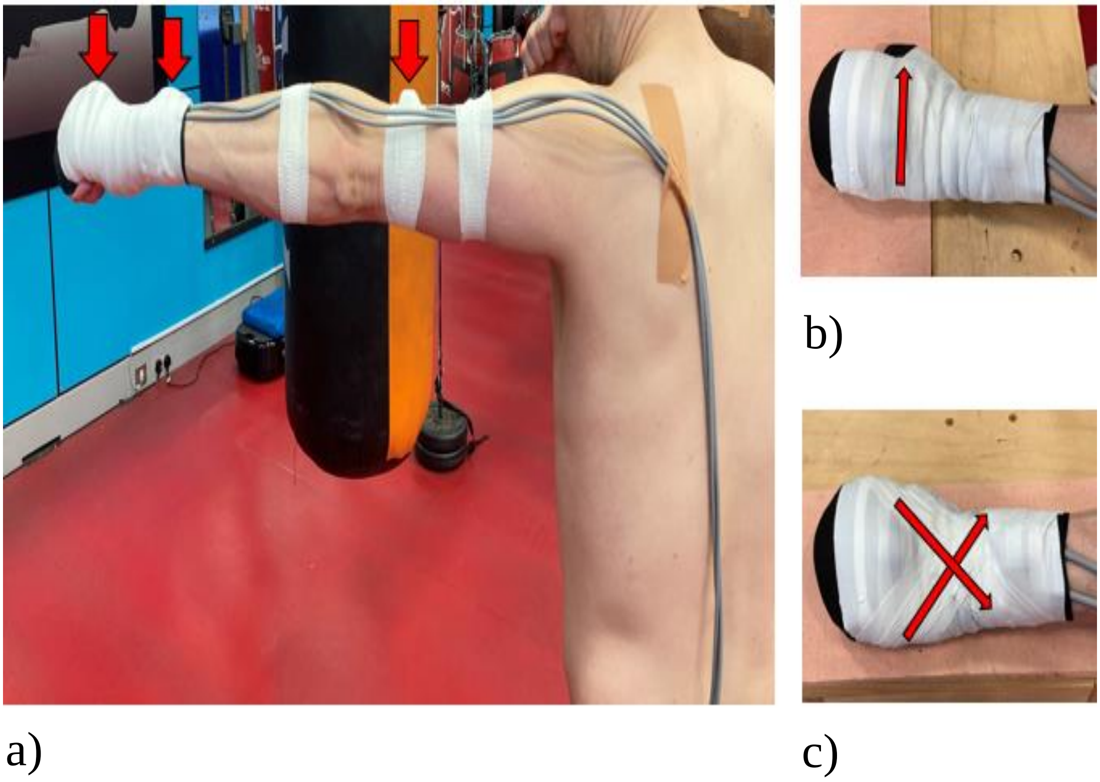


Figure 6.1: Electromagnetic tracking system placement and bandaging technique using rigid tape (Zinc oxide W: 2.5cm) added on top of the bandage technique (Figure 3.7) for quasistatic and impact testing with; a) receiver placement with the position for each receiver identified anatomically with arrows, b) on the hand and forearm using a continuous strip of rigid tape distally and finishing proximally at the hand and wrist region, ensuring that each strip of tape overlapped the previous strip by 50% of its width, providing approximately 12 revolutions around the hand-wrist region., and c) six strips of rigid tape (L: 20cm and W: 2.5cm) applied on top of the circular tape, creating a 3x criss-cross pattern. The strips, starting distally at the hand, were applied across the wrist finishing on the distal 1/3 of the forearm (i.e., a distal-to-proximal application of tape). The arrows in b) and c) indicate the direction the tape was applied. *Figure source (Gatt, Allen and Wheat, 2023).*

6.2.2.2. Impact Testing

Impact testing, to quantify wrist motion on impact, was performed using the same equipment as described before (Section 3.4.2.3). Similar to previous studies (Chapters 4 and 5), shots were performed six times, allowing a between-shot break of approximately three seconds, with the 2nd to 5th shots used for statistical analysis (Chapter 3). Boxers performed both shot types, Jab and Hook, in both bandaging conditions in the same session. Both order of bandaging techniques and shot types thrown were randomly assigned.

6.2.3 Data Processing, Analysis, and Definitions for Peak Wrist Angle, Time to Peak for Wrist Angle and Average Speed of Shot

The tracking system data from all testing procedures were processed and analysed following a similar protocol (Section 3.6), used in previous studies (Chapters 4, 5). Peak wrist angle on impact with the bag was identified using a previously defined manual method (Gatt, Allen and Wheat, 2020; Section 3.6). Further, the distance and time of shots thrown was assessed, using the same equipment (Section 3.6), to estimate the average speed of both shots (equation 1) and further account for effects on wrist motion. Time to peak angle for each shot was identified for this study.

Average speed of shot was calculated using the equation (1):

$$S = \frac{d_{PI} - d_{SS}}{t_{PI} - t_{SS}}$$

Key moments were; S (average speed of shot), d (distance), t (time), PI (point of impact of the hand on the boxing bag), SS (point the hand started moving towards the boxing bag). Distance and time from SS to PI were identified using a manual method (Figures 6.2 and 6.3) consisting of; i) visual observation of the virtual upper limb to identify movement along the path of either the z-axis or x-axis respectively for straight arm and bent arm shots, and ii) identify the point of hand impact observed at pre-terminal elbow extension for straight arm shots or pre-terminal shoulder horizontal adduction for bent arm shots, observed to occur prior to maximum x-axis wrist displacement. The stages of upper limb motion for both shots were classified and are provided visually for reference (Figures 6.2 and 6.3).

6.3 Statistical Analyses

The data from all testing procedures were analysed using a statistical spreadsheet (Jamovi v2.5.5, www.jamovi.org). Z-Scores for skewness and kurtosis were used to test for normal distribution of data with the threshold for the observed values set at ±2 standard deviations of the predicted values (Appendices). Data were analysed using Excel 2022 and Jamovi (Version 2.3.16.). For both wrist angular motions, FLEX and UD, two-factor (2×2) repeated measures Analysis of Variance (ANOVA), with Tukey's test for post-hoc analysis (a = 0.05), were performed to assess the effect of banding techniques (bandage only and bandage plus tape) and shot types (bent and straight arm). Similar analysis was performed for time to reach peak angle and average speed of shot. Further, for all four wrist motions (FLEX, EXT, UD, and RD) one-way ANOVAs, with Tukey's test for post-hoc analysis (a = 0.05), was performed to assess the effect of no bandaging and both bandaging techniques during quasistatic testing.

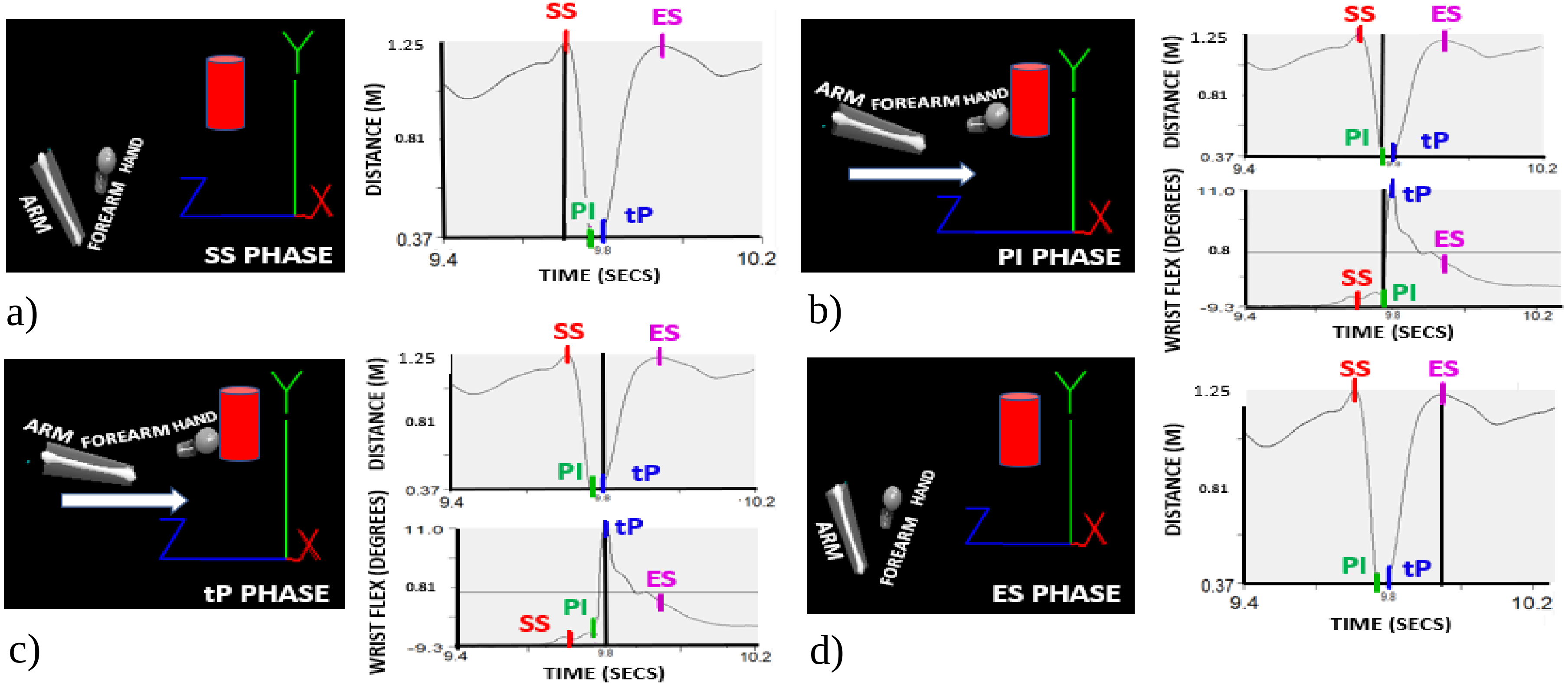


Figure 6.2: Visual representation of wrist kinematics occurring during different boxing phases prior to and on impact with a lead straight arm shot (Jab), quantified using Visual 3D software. On the left, computer generated model showing individual anatomical segments; arm, forearm, hand. A target (red cylinder) is included to indicate the location of the bag equipment. An arrow indicates the direction of upper limb movement against xyz orientation. On the right the path of the upper limb (using the hand segment relative to the source box) along the z-axis with event markers created to identify the sequence of shots; a) point when the hand begins to move in the direction of the target (SS), b) point of impact of the hand with the boxing bag (PI), c) time to peak wrist angle on impact (tP), and d) point when the hand returns back to original starting position (ES). At both PI and tP phases wrist FLEX-EXT (x-axis) is included to show corresponding wrist motion on impact with boxing upper limb phases. *Figure source from Gatt, Allen and Wheat (2023).*

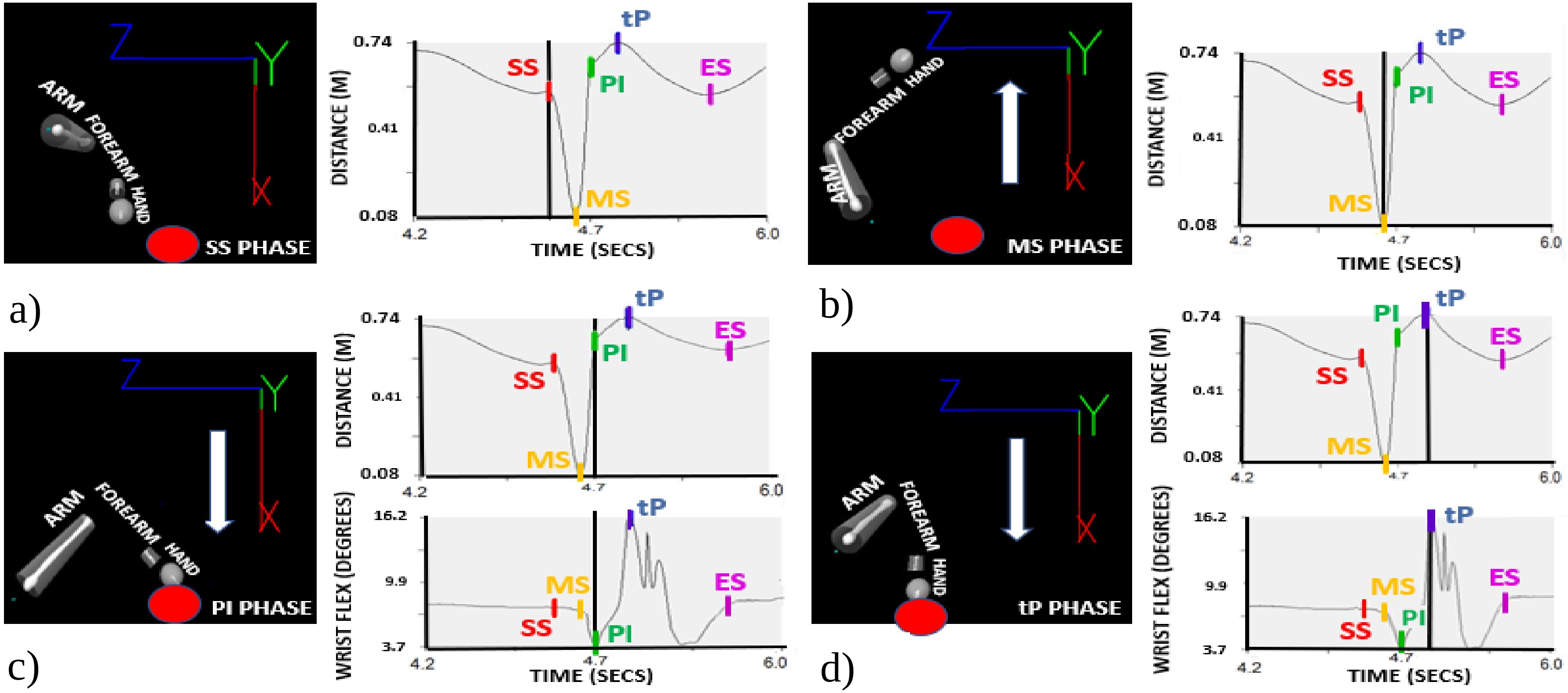


Figure 6.3: Visual representation of wrist kinematics occurring during different boxing phases prior to and on impact with a lead bent arm shot (Hook) using Visual 3D software. On the left, computer generated model showing individual anatomical segments; arm, forearm, hand. A target (red circle) is included to indicate the location of the bag equipment. An arrow indicates the direction of upper limb movement against xyz orientation. On the right the path of the upper limb (using the hand segment relative to the source box) along the x-axis with event markers created to identify the sequence of shots; a) point when the hand begins to move in the direction of the target (SS), b) mid-phase of shot showing the hand moving in the opposite direction of the target (MP), c) point of impact of the hand with the boxing bag (PI), and d) time to peak wrist angle on impact (tP). At both PI and tP phases wrist FLEX-EXT (x-axis) is included to show corresponding wrist motion on impact with boxing upper limb phases. *Figure source from Gatt, Allen and Wheat (2023).*

All data are presented as means ± standard deviations. The magnitude of any differences (effect size) was assessed using Eta Squared (η^2) with the following benchmarks: *small* (η^2 = 0.01), *medium* (η^2 = 0.06), and *large* (η^2 = 0.14) (Lakens, 2013).

6.4 Results

6.4.1 Impact Testing

All data for shot types were normally distributed with 95% of the observations falling inside the predicted Z-Scores.

6.4.1.1 Peak Wrist Angles

Wrist angular motions occurred concurrently in FLEX and UD for both shot types. A 2x2 ANOVA with Eta Squared (η^2) revealed a significant ($p<0.001$) interaction between bandaging techniques and shot types for both wrist motions, FLEX and UD (Appendices). Main significant ($p<0.001$) large effects for wrist motions of FLEX and UD were observed for both shot types (η^2 = 0.165-0.280) and bandaging techniques (η^2 = 0.580-0.729) (Figure 6.4 and Appendices). A Tukey post-hoc analysis showed that both FLEX and UD motions differed significantly ($p<0.001$) for both shot types and bandaging techniques (Table 6.1). Bandage plus tape reduced wrist motion compared to bandage only, and more motion occurred at the wrist with straight than bent arm shots (Figure 6.4). For straight arm shots, all wrist angular motions on impact occurred within 50% of TROM for bandage only and 20% of TROM for bandage plus tape. For bent arm shots, all wrist motions on impact occurred within 40% of TROM for bandage only and 15% of TROM for bandage plus tape.

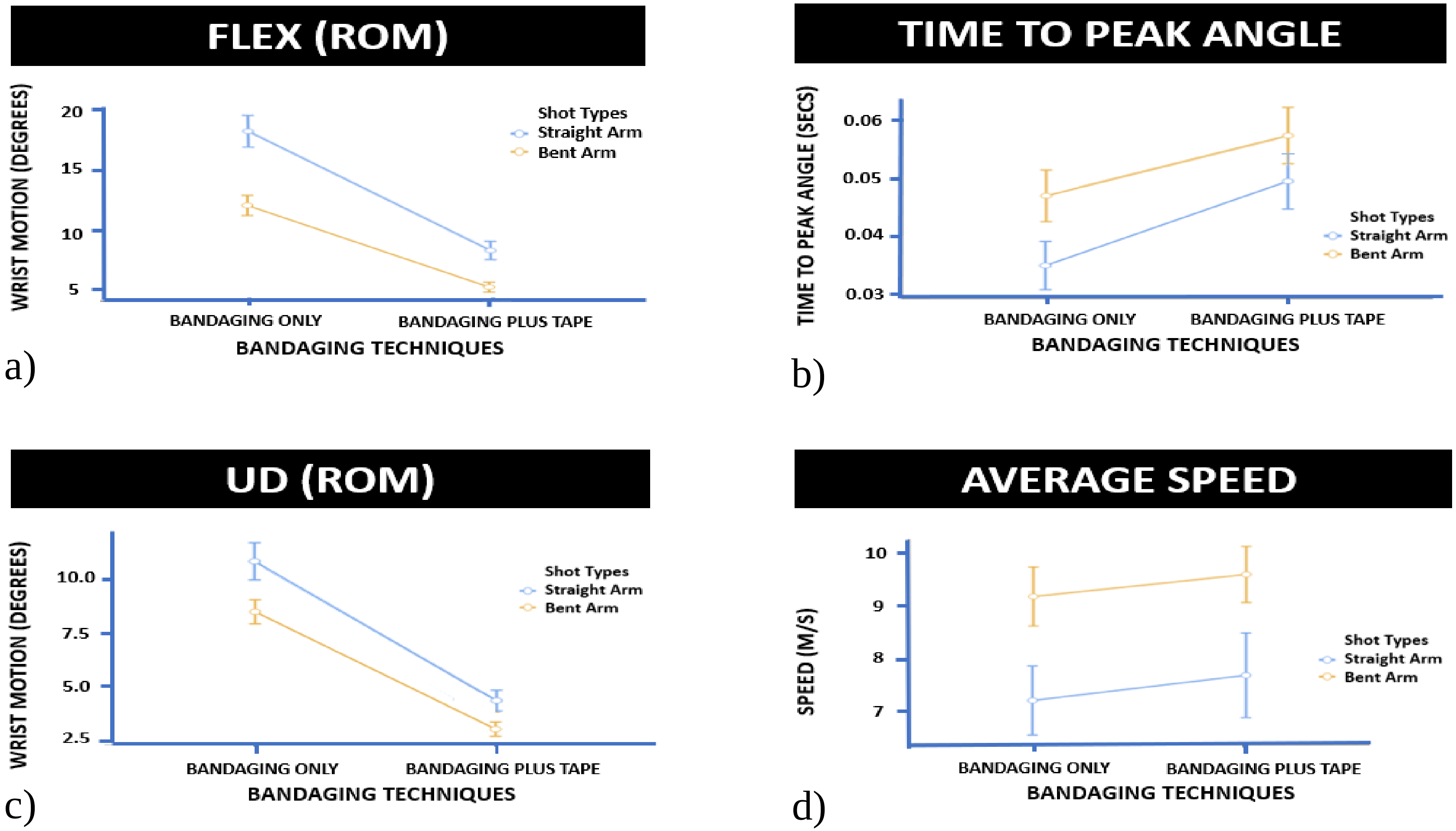


Figure 6.4: Effect of bandaging techniques on; a) wrist FLEX angular motion, b) wrist UD angular motion, c) time to peak wrist angle, and d) speed of shot. Error bars represent between-participants standard deviation. *Figure source from Gatt, Allen and Wheat (2023).*

Table 6.1: Tukey post-hoc analysis for FLEX (degrees) and UD (degrees) motions, time to peak wrist angle (seconds), and average speed of shot (m/s). *Table source from Gatt, Allen and Wheat (2023).*

		Mean Difference	**df**	**t**	**Ptukey**
FLEX	Shot Types	5.7	17	8.8	<0.001
	Bandaging Techniques	8.2	17	50.4	<0.001
UD	Shot Types	2.9	17	10.5	<0.001
	Bandaging Techniques	6.1	17	31.1	<0.001
Time to Peak Wrist Angle	Shot Types	-0.01	17	-4.44	<0.001
	Bandaging Techniques	-0.012	17	-8.75	<0.001
Average Speed of Shot	Shot Types	-1.91	17	-8.01	<0.001
	Bandaging Techniques	-0.439	17	-4.03	<0.001

6.4.1.2 Time to Peak Wrist Angles

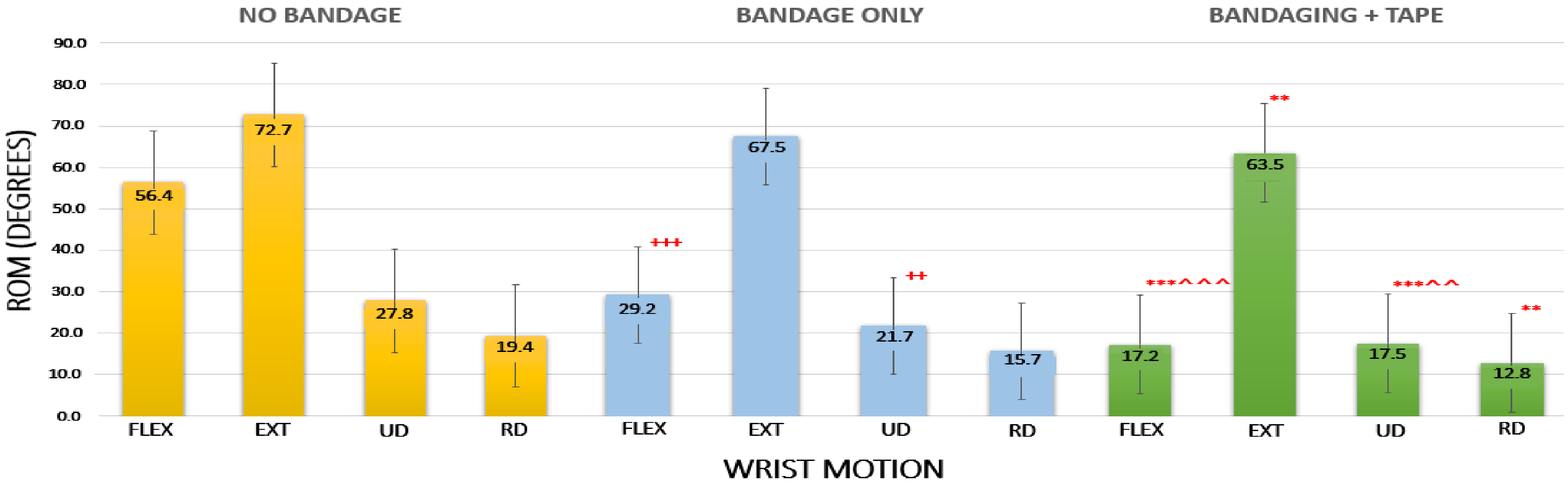
A 2x2 ANOVA with Eta Squared revealed a non-significant (P=0.146) interaction between bandaging techniques and shot types for time to peak wrist angles (Appendices). Main significant (p<0.001) large effects were observed for time to peak wrist angles for both shot types ($\eta^2 = 0.170$) and bandaging techniques ($\eta^2 = 0.267$) (Figure 6.4 and Appendices). A Tukey post-hoc analysis (Table 6.1) showed that time to peak wrist angles differed significantly (p<0.001) for both shot types and bandaging techniques. Bandage plus tape increased time to peak wrist angles on impact compared to bandage only, with time to peak wrist angles on impact longer in bent than straight arm shots. Mean times to peak wrist angles for straight arm shots were 0.035 and 0.049 seconds respectively for bandaging only and bandaging plus tape, and for bent arm shots were 0.047 and 0.057 seconds respectively for bandaging only and bandaging plus tape. The mean time to peak wrist angles on impact increased by 1.4 and 1.2 times for straight and bent arm shots respectively when adding tape to bandaging.

6.4.1.3 Average Speed of Shot

A 2x2 ANOVA with Eta Squared revealed a non-significant ($p=0.801$) interaction between bandaging techniques and shot types for average speed of shot (Appendices). Main significant ($p<0.001$) large and small effects respectively were observed for shot types ($\eta^2 = 0.365$) and bandaging techniques ($\eta^2 = 0.019$) for average speed of shot (Figure 6.4 and Appendices). A Tukey post-hoc analysis (Table 6.1) showed that average speed of shot differed significantly ($p<0.001$) for both shot types and bandaging techniques. Average speed for straight arm shots were 7.2 and 7.7 m/s respectively for bandaging only and bandaging plus tape, and for bent arm shots were 9.1 and 9.6 m/s respectively for bandaging only and bandaging plus tape.

6.4.2 Quasistatic Testing

A one-way ANOVA with Eta Squared for bandaging techniques revealed significant ($p<0.001$) large effects for all wrist motions; FLEX ($p<0.001$, $\eta^2 = 0.850$), EXT ($p<0.011$, $\eta^2 = 0.163$), UD ($p<0.001$, $\eta^2 =386$), and RD ($p<0.002$, $\eta^2 = 0.210$), with FLEX showing the largest effect (Figure 6.5 and Appendices). A Tukey post-hoc comparison showed significant differences between bandaging only and bandaging plus tape for FLEX and UD motions, but not for EXT and RD.



Significant differences between:

i. Bandaging only and No Bandaging; $^{+}p<0.05$, $^{++}p<0.01$, $^{+++}p<0.001$

ii. Bandaging plus Tape and No Bandaging; $^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

iii. Bandaging plus Tape and Bandaging Only; $^{\wedge}p<0.05$, $^{\wedge\wedge}p<0.01$, $^{\wedge\wedge\wedge}p<0.001$

Figure 6.5: Effect of bandaging techniques during the quasistatic testing on wrist ROM. Error bars represent between-participants standard deviation. Significant differences indicated. *Figure source from Gatt, Allen and Wheat (2023).*

6.5 Discussion

The effect of active ROM reduction by taping procedures has been shown at the wrist during activities of daily living (Mojaeva, McAlonan and Scott, 2022), and at the ankle during exercise and drop landing activities (Purcell et al., 2009; Sato et al., 2019). In boxing, although adding tape to bandage can constitute part of normal routine at some competitions, and sometimes during training, no study to date has identified whether it influences wrist motion. This study quantified wrist motion on impact in boxing using two bandaging techniques. Adding tape to the bandage provided an additional 25-30% reduction in wrist angular motion on impact compared to bandage only, for both straight and bent arm shots. These results confirm the primary hypothesis of this study that less wrist angular motion on impact occurs when tape was added to a traditional bandage technique for both shot types.

Although it is assumed that taping might alter joint kinetics, no studies have been identified at the wrist. As mentioned in Chapter 2, ankle joint moments have been observed to be significantly reduced when adding tape to an ankle during jump landing activities (Sato et al, 2019). Wrist guards used for snowboarding, which are a more rigid structure than tape, reduced peak force by at least 24% and increased time to peak angle by at least 1.8 times, when applied to a surrogate wrist in a mechanical impact test (Adams et al., 2021). Comparatively in this current study, adding tape to bandage, during *in vivo* testing, increased time to peak wrist angles by 1.2 to 1.4 times for both shot types. Forces or joint moments were not investigated. However, a reduction in joint moments might be expected when adding tape to bandaging, considering a decrease in wrist angular distance alongside an increase in time to peak wrist angles. Future studies should assess joint kinetics on impact, particularly as the role of hand-wrist protection has been considered in various activities and sports, using more rigid support (Hwang et al., 2006; Michel et al., 2013; Burkhart and Andrews, 2010), yet studies towards hand-wrist injury reduction are still lacking in boxing.

In the quasistatic testing, ulnoflexion motion was significantly reduced when adding tape to the bandage, agreeing with the results from the impact testing. However, no difference was observed in EXT and RD. In the quasistatic testing, all motions showed a significant difference between bandaging plus tape and no bandaging, as compared to bandaging only and no bandaging, where only FLEX and RD motions were significantly reduced. The taping method used a circular followed by a cross-cross technique (Figure 3.10). The circular technique is not widely considered, from clinical practice, to have a direction specific effect on reducing wrist ROM. This might explain the reduction observed in all motions in the quasistatic testing between bandaging plus tape and no bandaging. Conversely, the criss-cross technique was aimed at mainly reducing FLEX and UD, the motions occurring on impact as observed in Chapter 5. The significant reduction in FLEX and UD motions, when comparing bandaging plus tape and bandaging only, agrees with other studies where specific direction of taping limits the intended motion (Mojaeva, McAlonan and Scott, 2022; Purcell et al., 2009; Sato et al, 2019). Assessing the effect of bandaging techniques on reducing wrist motion is therefore recommended using a quasistatic method, as this approach can be a quick method, especially when considering accessibility of widely used methods for measuring wrist motion (Surangsrirat et al., 2022).

Shot types also influenced the amount of wrist angular motion on impact. Wrist angles were greater in both FLEX and UD for straight than bent arm shots (Figure 6.3). This finding confirms the second hypothesis of this study that more wrist angular motion on impact occurs in straight than bent arm shots, for both bandaging techniques. This finding agrees with a previous study where bandage only was used (Chapter 5), whilst further showing the influence, when adding tape, of shot types on wrist motion.

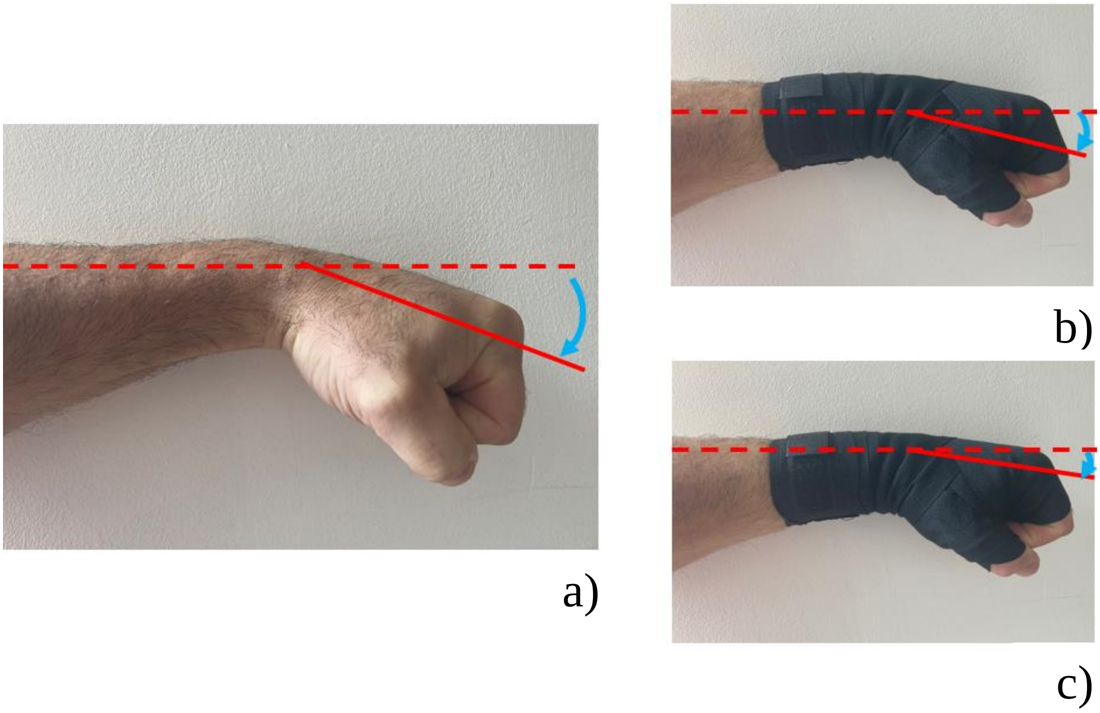
From the results obtained in this study, both bandaging techniques and shot types showed main effects for both wrist motions, FLEX and UD, during impact testing. Further, a significant interaction between bandage technique and shot type was observed for both wrist motions, however, with larger effects observed for taping techniques compared to shot types for both wrist motions (Table 6.4 and Appendices). The highest difference, occurring with FLEX motion, resulted from the effects of straight arm shots and bandaging plus tape. This is important considering that straight arm shots have been identified as incurring a higher prevalence of injury compared to bent arm shots (Chapter 2). The clinical implication is that to reduce wrist motion, specifically FLEX during straight arm shots, adding rigid tape to a bandage will have the largest interaction.

Average speed of shot was higher in bent arm (9.1-9.6 $m.s^{-1}$) than straight arm (7.2-7.7 $m.s^{-1}$) shots. Conversely, delivery times (SS to PI) were slower for bent arm (0.119-0.129 seconds) than straight arm (0.106-0.112 seconds) shots. This can be explained by the upper limb segment sequencing, mentioned before in Chapter 5, where a proximal-to-distal sequence between the elbow and wrist joints is not observed due to fixed elbow positions in bent arm shots (Stanley et al., 2018). During straight arm shots (Figure 6.1), the elbow joint straightens rapidly as it accelerates towards the target via angular velocities generated at the shoulder joint (Cheraghi et al., 2014).

Conversely during bent arm shots (Figure 6.2), the elbow is fixed to an appropriate right angle whilst the shoulder exhibits a large amplitude of motion (Piorkowski, Lees and Barton, 2011). As more wrist angular motion occurs in straight than bent arm shots, whilst higher velocities occur in bent than straight arm shots (Dinu et al., 2020; Piorkowski, Lees and Barton, 2011; Whiting, Gregor and Finerman, 1988), other factors affecting wrist motion on impact need to be considered.

In this study, changes in wrist angular motion were observed with both bandaging techniques, which could not solely be accounted for by passive restriction. For FLEX ROM, adding bandage during the quasistatic testing reduced wrist motion by 52% of TROM (i.e., AROM) (Figure 6.6b) In the impact testing, this motion was observed as 33% and 22% respectively of TROM for straight and bent arm shots (Figure 6.6c). The difference in wrist motions observed between the impact (Figure 6.6c) and quasistatic (Figure 6.6b) testing conditions, is likely due to wrist active stability or dynamic control (i.e., muscle function) rather than passive restriction (i.e., bandaging materials). When adding tape to the bandage, a difference was also observed between both testing conditions, for both shot types. Similar to bandage only, this difference could not be attributed solely to passive restrictions of bandage plus tape. However, with increased passive restriction, by adding tape to the bandage, a smaller difference was observed between the motion on impact and AROM compared to bandage only. Similar differences to FLEX were also noted for UD in both bandaging techniques. The potential implication is that less dynamic control may be required, towards wrist stability on impact, with increased passive restriction (i.e., adding tape). Motion compensations can be challenging to understand, but they are clinically observed phenomena around joints and identified especially with pathologies (Bauman and

Chang, 2013; Khandare, Arce and Vidt, 2022). The effect of active stability at the wrist could be important in understanding the differences in wrist angular motion on impact, observed between straight and bent arm shots. Equally the effect of active vs passive stability could have a role towards understanding the mechanism of injuries in competitions where less support at the wrist is available, due to regulations limiting the type and amounts of materials, as compared to training. However, it is important to acknowledge that beyond active stability acting at the wrist, adding bandage only or bandage plus tape can reduce the amount of wrist motion through the mechanical properties of the materials used. On impact, these materials can absorb forces, reducing these forces acting on the wrist, and likely reducing the effect on inducing motion at this joint. Further discussion on materials is provided in Chapter 7.



6.6: Wrist active stability depicted using wrist FLEX motion, from the side, showing; a) TROM (i.e., the total active ROM available in quasistatic without use of bandage), b) AROM (i.e., the total active ROM available in quasistatic when adding either bandage only or bandaging plus tape, in this case bandage only being shown), c) ROM on impact occurring with either Jab or Hook shots with either bandage only or bandaging plus tape, in this case bandage only being shown). Dashed red line indicating neutral or zero position, solid red line indicating end position relative to dashed line, and blue arrow depicting arc and direction of motion. Note that the ROM in a > b > c. The difference between c and b is proposed to be occurring due to active or dynamic control.

At the shoulder and ankle joints, adding tape has been observed to improve proprioception, assessed as JPS (Park et al, 2020; Alawna, Unver and Yuksel, 2021). At the wrist, one study assessed JPS using either bandage only (i.e., standard therapeutic bandage) or rigid tape, using a hypoallergenic tape to protect the skin (Ucozuglo., 2020). Ucozuglo et al. (2020), observed an increase in JPS for both conditions. These observed differences from Ucozuglo et al. (2020), could justify the observations made in this current study. Dynamic wrist control, influenced by JPS, is likely affecting wrist motion on impact in boxing in combination with passive restriction of applied materials at the hand-wrist. In the study by Ucozuglo et al. (2020), no significant differences between conditions (bandage and tape) were observed, however, rigid tape improved FLEX JPS significantly more compared to bandage, 20 minutes after application. However, Ucozuglo et al. (2020) observed differences between taping and no taping at the joint, compared to the current study where differences between bandaging with tape and bandaging only of the joint were considered. Further discussion on dynamic wrist stability is provided in Chapter 7.

There are other factors which are worth considering. The amount of wrist motion occurring on impact may be influenced by boxing experience. For bandaging only, this study observed less than 50% and 40% of TROM for straight and bent arm shots, respectively. This is greater than the previous study (Chapter 5), using bandage only, which observed less than 30 and 20% of TROM for straight and bent arm shots respectively. Participants in the current study were less experienced (< 3 years on the GB Squad) than participants in the previous study (> 5 years on the GB Squad) (Chapter 5). Dinu and Louis, (2020) observed more motion occurring at both the shoulder and trunk in less experienced boxers, when throwing both straight and bent arm shots. In their study, less experienced boxers were able to produce only about a third of the force when compared with more experienced boxers, whilst the shot speed, although significantly lower, was closer (Dinu and Louis, 2020). Whether it is the ability to generate force, or specific technical aspects when throwing shots, it appears that experience can influence the amount of motion occurring at different joints, which includes the wrist. Improving wrist support, especially for less experienced boxers, should therefore be a priority at both training and competition. Experience has been discussed before in Chapter 2, with further discussion provided in Chapter 7.

Although there was a significant effect ($\eta^2 = 0.365$, $p<0.001$) in average speed between shot types, when adding tape to bandage the effect ($\eta^2 = 0.019$, $p<0.001$) was too small to be considered meaningful. When adding tape to bandage, the average speed increased from a mean and standard deviation of 7.2±1.2 to 7.7±1.5 m/s in straight arm shots, and from 9.1±1.1 to 9.6±1.0 m/s in bent arm shots. Wearing tape has been shown to increase grip strength, however, the authors describe the effect as trivial and indicate a placebo (i.e., psychological) rather than a true physical effect (Mak et al., 2019). Whether the effect on shot average speed observed in this current study was a physical or placebo attribute, and could this effect increase in other training settings or competition, is beyond the scope of this study. It is useful however, to consider whether having more support at the wrist enables more confidence towards throwing shots.

There are methodological limitations that should be acknowledged. The approach to this study was aimed at controlling forces, although not objectively assessed with a device such as a punch dynamometer, (Diewald et al., 2022), by asking participants to throw shots at submaximal intensity levels. This approach was performed to improve ecological validity (Andrade, 2018), reflective of their normal training behaviour, and limit the risk of injury to participants (Chapter 3). Most studies, however, typically consider a maximal intensity approach (Dinu et al., 2020; Kimm and Thiel, 2015; Whiting, Gregor and Finerman, 1988). However, the results of this current study show that the average speed of the straight arm shot (7.2±1.2 to 7.7±1.5 $m.s^{-1}$), thrown at submaximal effort, was within 89-95% of the average speed (8.1±1.4 $m.s^{-1}$) of another study where maximal effort was measured from beginning to end of shots thrown in the air (Kimm and Theil, 2015). Therefore, there is confidence in the speeds of the shots thrown by the participants in this study to be as intended, submaximal (i.e., just below maximal intensity).

No blinding of the participants was performed towards their knowing which bandaging technique was used, which could have influenced their approach towards throwing shots. Blinding the participants to the type of bandaging technique is however questionable, as experienced boxers would feel the difference between the two techniques used in this study. Although bias might have been present, an approach to reduce this bias was by randomly assigning the order of shot types and bandaging techniques for participants.

No bandaging was used in one of the quasistatic testing conditions, to assess TROM available at the wrist. However, punching with no bandaging was not performed during the impact testing, as it is not a typical practice used in training. Further this approach would be considered unsafe. The bandage is also important to secure the electromagnetic receivers and reduce angle measurement error which can occur due to excessive skin movement (Chapter 3).

Further limitations, which apply to both studies, conducted in Chapters 5 and 6, will be discussed in Chapter 7.

6.6 Chapter Conclusion

This chapter showed an interaction between bandaging techniques and shot type, and main effects of bandaging techniques on wrist kinematics on impact when throwing straight and bent arm shots on a commonly used type of training equipment. Wrist angular motions occurred concurrently in FLEX and UD for both shot types. Adding tape to a traditional bandage technique provided an additional 25-30% reduction in wrist motion on impact compared to bandage only, with a 1.2-1.4 increase in time to peak for wrist angle, with a greater effect during straight than bent arm shots. Adding on from the study conducted in Chapter 5, the results from this study improve the understanding of hand-wrist injury reduction and management strategies. This information could assist athletes, coaches, wider public and boxing associations in their decision making, with a consideration towards rule making, which can influence improved support of the hand-wrist region during punching activities. Further conclusions, on the practical implication of the findings in this, and previous chapters (Chapters 4 and 5), is provided in the next chapter.

7.0 General Conclusions

7.1 Introduction

Building on the results from studies conducted (Chapters 4 to 6), and wider learning throughout the programme of research, this chapter aims to establish the significance of the knowledge acquired within the broader academic and practical context. It will emphasise how the findings advance existing knowledge, filling gaps, or offering new perspectives. Overall, this final chapter of this programme of research serves as a platform for critical analysis, interpretation, and reflection of the findings.

7.2 What has been Achieved and Practical Implications.

Through extensive clinical practice it has been observed that wrist motion on impact can provide an important factor towards injury of the CMC joint, whilst also acknowledging the effect of wrist motion on other hand-wrist injuries. As discussed in Chapters 1 and 2, taping is allowed in training, whereas there are currently restrictions during international competition in amateur style boxing. Further, from clinical practice it has been anecdotally observed that these CMC injuries can be better managed, when occurring, by using taping techniques or more rigid devices like braces. The inference was that limiting wrist motion, specifically FLEX, on impact would be an important factor in reducing the risk of CMC injuries. Forced FLEX is the mechanism identified when injuries of these CMC joints occur (Matharu et al., 2022a; Noble, 1987;), however, prior to this programme of research in-vivo impact testing had not been performed to quantify what motion occurs. It was therefore critical to understand how wrist motion could be measured in various situations, namely training using bag equipment, but also consider the implications for other situations like sparring in training and competition.

Although it could be assumed that the ideal scenario would be assessing wrist kinematics in all the various training and competition scenarios, a programme of research needs to have a chronological sequence when approaching studies, ensuring appropriate scientific rigour is maintained. Most studies assessing kinematics in boxing, looking at joints other than the wrist, have used training-based scenarios using a static or quasistatic object (i.e., wall mounted dynamometer or training bag) (Bergün et al., 2017; Dinu and Louis, 2020; Stanley et al., 2018; Whiting, Gregor and Finerman, 1988). It was therefore deemed appropriate to follow a similar approach to these studies by using a training bag. This approach allowed for comparison of metrics and observations obtained from the studies conducted in this programme of research. No studies, before this programme of research, had quantified the kinematics of boxing in sparring or competition conditions. A plan of studies was formulated, with aims and objectives clearly identified (Chapter 1), whilst also appreciating what limitations could be present from the inception to conclusion of the project.

7.2.1 Novel Methodology to Quantify Wrist Motion on Impact

The first study (Chapter 4) achieved accuracy and repeatability of a method, using an electromagnetic system, to effectively measure wrist motion on impact for boxers on a boxing bag. The results allowed progression onto subsequent studies. Beyond this programme of research, this methodology provides a novel method for other researchers to consider for the assessment of wrist motion in various occupational and sporting activities. Especially in conditions where direct line of sight is not viable, this methodology will enable researchers to consider potential use. Further, results from the study provide metrics for future studies assessing validity and reliability of systems aimed specifically for wrist motion. The contribution to the wider research community therefore transcends the initial objectives set for this programme of research.

7.2.2 Type of Motion Occurring on Impact

The second study (Chapter 5) confirmed that FLEX motion occurs on impact in boxing. Further, this study also confirmed that UD occurs concurrently with FLEX on impact. These findings support the DTM (i.e., ulnoflexion to radioextension), which typically occurs in activities of daily living and sports (Chapter 2). These findings were further supporting in the third study (Chapter 6). This information adds to the wider knowledge on DTM from various non-boxing studies. It also allows new information to support why certain areas, namely 2nd and 3rd CMC joints, get injured compared to 4th and 5th CMC joints (Chapter 2). This study (Chapter 5) also generated the requirement for further research aimed at identifying if reducing this motion is feasible, supporting the rationale for progressing to the following study (Chapter 6).

7.2.3 Kinematic Considerations towards Wrist Motion on Impact.

Injuries at the hand can occur with both types of commonly used shots in boxing, straight and bent arm. From the data collected at GB boxing since 2010 till present, it has been observed that straight arm shots contribute more to CMC joint injuries than bent arm shots. It was therefore proposed that straight arm shots would exhibit more wrist angular excursion on impact than bent arm shots. This was confirmed in this programme of research (Chapters 5 and 6). The practical implication is that straight arm shots, although generating lesser terminal velocity prior to impact than bent arm shots (Stanley et al., 2018), can lead to more hand-wrist injuries than bent arm shots. This would appear a paradox, as more velocity should likely induce more wrist excursion on impact. However, as discussed in Chapter 2, a proximal-to-distance sequence of the upper limb joints (i.e., shoulder-to-elbow) occurs in straight arm as compared to bent arm shots where this sequence is not observed. This proximal-to-distance sequence is not observed with bent rm shots due to the elbow joint peak velocity occurring prior to that of the shoulder joint (Stanley et al. 2018). On impact the elbow joint is almost static for bent arm shots, whereas it is moving during straight arm shots (Stanley et al., 2018). The muscles which actively control wrist ulnoflexion, ECRL and ECRB, cross both wrist and elbow joint (Chapter 2). More active stability (Chapter 2) is likely occurring at the wrist with bent arm than straight arm shots on impact.

Beyond the local motion of joints, a consideration of the interaction of the more proximal joints, elbow and shoulder, is required. Factors like strength and stability at these more proximal joints, together with technique, may need to be considered for boxers. The practical implications here are towards future studies to potentially identify whether wider body kinematics and/or kinetics influence wrist motion on impact. These considerations will be discussed further in section 7.4.

7.2.4 Magnitude of Shot on impact and Influence of Athlete Experience

When using cotton bandaging only, the magnitude of wrist motion observed in this study (Chapter 6) exceeded that of the previous one (Chapter 5). For bandaging only, when throwing straight and bent arm shots, this study observed less than 50% and 40% respectively of TROM as compared to the previous study with less than 30% and 20% respectively. Participants in this study (Chapter 6) were less experienced (< 3 years on the GB Squad) than participants in the previous study (Chapter 5) (> 5 years on the

GB Squad). Of note, more injuries are typically observed anecdotally at the hand-wrist region with boxers having lesser experience as part of the GB Squad. Further the prevalence of hand-wrist injuries in the same boxers has been anecdotally observed to decrease as their experience improves over the years on the GB Squad. This difference in injury prevalence could be due to less experienced athletes taking less responsibility when making decisions linked to injury prevention strategies (Bonell-Monsonis et al, 2021). In contrast, experienced athletes would typically acquire more understanding and responsibility, allowing autonomy and independence in their decisions around sports preventive strategies (Bonell-Monsonis et al, 2021).

In some non-boxing studies, athletes with higher experience are prone to a higher prevalence rate of injuries, although it appears this is linked to higher training hours rather than experience (Alekseyev et al., 2020; Zetaruk et al., 2005; 2000). More experienced and established athletes are also more likely to return to competition at the same level after a serious injury than less experienced athletes (Shah et al., 2010), reducing loss in training availability. This difference in return to sport, between athlete experience, is likely linked to mindset which can influence the severity of an injury (i.e., training availability after an injury occurs).

Although experience was not an independent variable proposed from the onset of this programme of research, the comparative data between the two studies (Chapter 5 and 6) are worth acknowledging. Kinematic differences have been observed in boxing in the upper limb, with greater motion occurring in less as compared to more experienced boxers (Dinu and Louis, 2020). These kinematic differences agree with the results obtained between the two studies conducted in this programme of research (Chapters

5 and 6). In these studies (Chapter 5 and 6), greater wrist ROM on impact was observed in more experienced boxers. In snowboarding, another sport which incurs many wrist injuries, beginners tend to suffer more impacts from falls resulting in higher maximum loads generated at the wrist (Greenwald, Simpson and Michel, 2013). Experience could therefore be an important factor to consider with hand-wrist injury trends amongst boxers.

7.2.5 Effect of Taping on Wrist Motion and the Interaction with Shot Type

For straight and bent arm shots, wrist motion occurred within 50% and 40% respectively of TROM for bandage only compared to within 20% and 15% for bandage plus tape (Chapter 6). These results confirm that adding tape to bandage can be an important factor towards reducing the magnitude of wrist motion on impact. In this study, a significant interaction was also observed between bandaging technique and shot type on wrist motion on impact. When adding tape to a bandage, straight arm shots were observed to reduce wrist motion more than bent arm shots. Considering that straight arm shots have been anecdotally linked to more hand-wrist injuries compared to bent arm (Chapters 2), this information can support preventative strategies.

Although a higher incidence of hand-wrist injuries is observed in competition than training, similar type of injuries occurs (Chapter 2). The practical implication is that although the methodology used in this study was not feasible towards use in competition (Chapter 2), it would be expected that adding taping to bandaging similarly reduce wrist motion, and therefore reduce the injury risk. This is further supported by the higher injury incidence rates observed at international amateur boxing competitions when bandage only is allowed, compared to adding tape. The use of tape in all competition formats is therefore advocated with international associations required to consider health above economic cost, when implementing rules.

Beyond the magnitude of wrist motion, tape increased the time to peak wrist angle, as confirmed from this programme of research (Chapter 6). This potentially enables improved active wrist control on impact, especially with straight arm shots which are known to reach the target in the shortest time, compared to other shots (Stanley et al., 2018; Dinu and Louis, 2020).

The mechanical properties of the materials used, which can influence wrist motion beyond their physical properties (i.e., energy absorption beyond the rigid nature of the material), need to be acknowledge. In other studies, using a hand surrogate during impact testing, time to peak joint angle increased when using snowboarding wrist protectors (Leslie at al., 2023; Adams et al., 2021). Adams et al. (2021) observed that about 20–40% of the kinetic energy at impact was absorbed by the protectors. This included stretching of the fabric, friction during sliding, hysteresis during compression of padding and bending of splints. Adams et al. (2021) observed that products returning the lower peak vertical forces tended to take longer time to reach this peak. Most products returning lower peak vertical forces also took longer to reach the time to peak joint angle. This increase in time to peak wrist angle is therefore likely due to lower forces acting at the hand-wrist region, resulting from the rigid tape absorbing some of the kinetic energy on impact. Less kinetic energy, absorbed by the hand-wrist anatomical structures, could be an important factor towards reducing potential injuries especially in a sport like boxing, where high forces are recorded at the hand-wrist region on impact (Chapter 2).

Adams et al. (2019) observed that peak vertical forces were lowest for the first impact for 73% of the protectors, indicating potential degrading of materials. This finding suggests that protectors may need replacing after a severe fall onto the hand. Fumich et al. (1981) observed that when applying tape to an ankle joint, the amount of ROM restriction gained, immediately after application, reduced when reassessed post exercise. In this study, the rigid tape was applied directly to the skin and the exercise described was a football game lasting up to three hours. In contrast, in boxing rigid tape is applied on the bandage, reducing the effect that sweat can have on loosening tape. Further, boxing training or competition would typically last less than an hour. The effect of rigid tape loosening or material degrading is however important, as it could influence injury reduction strategies when considering the use of these materials in boxing. The practical implication is towards boxers who wear the same bandage material, applied for a competitive event, in subsequent training events. This is a common cost saving practice used by some professional boxers. However, this practice could be counterproductive towards reducing the risk of injury due to the materials likely degrading over time. Further, the economic cost of managing significant hand-wrist injuries would be higher than using new materials, like rigid tape, for training. In competition, new materials are currently always used which remains an important strategy towards injury reduction.

7.2.7 Effect of Bandaging Techniques on Dynamic Wrist Control

As discussed in Chapter 6, with increased passive restriction, by adding tape to the bandage, a smaller difference was observed between the motion on impact and AROM when compared to bandage only (Figure 6.6). This could be explained by less active control (i.e., muscle stiffness) being produced with the bandaging plus tape condition as compared to the bandaging only. The clinical implication is that with less muscle stiffness, less muscle effort will be required, likely providing less fatigue in the forearm musculature controlling the wrist. Conversely the opposite can occur with too much muscle activity, occurring to limit wrist displacement, which can result in early-onset fatigue and potentially lead to injury (Foreman et al., 2020).

A reduction in the requirement for active stability, due to increased passive stability from using rigid tape, could possibly lead to an overall reduction in joint stability. In a study at the wrist, a robotic device delivered perturbations to the hand in the radial and ulnar directions across four pre-perturbation grip magnitudes (Manella et al., 2022). In this study, an inverse relation was observed between grip force, assessed isometrically using a custom grip force handle equipped with a force transducer, and angular displacement. Further, time to peak wrist angle displacement decreased as grip force increased (Manella et al., 2022). Increasing grip force has also been shown to increase forearm muscle activity (Mogk and Keir, 2003) and co-contraction (Holmes, Tat and Keir, 2015), which are considered factors of wrist stability (Salva-Coll et al., 2011).

Applying rigid tape to the hand-wrist region could influence the magnitude of peak force exerted by the wrist. The peak force exerted by the wrist, assessed using an isokinetic machine, was observed to be significantly decreased in FLEX by 14% and UD by 8% when applying rigid tape to the hand-wrist region (Kauranen, Siira, and Vanharanta H, 1997). In this study however, a decrease in average force for these motions was not significant. Of note, there was no effect on EXT or RD peak or average forces when applying rigid tape. Considering EXT and RD limit ulnoflexion motion at the wrist on impact (Chapter 2), applying tape would not have a detrimental effect on the ability to generate peak or average grip force.

In another study, MVC grip force was significantly reduced when applying tape to the wrist (Mojaeva, McAlonan and Scott., 2022). Grip strength appeared to follow a similar trend to static ROM. When more ROM was restricted, a larger difference was observed in MVC grip force. Taping on the dorsum of the hand to restrict FLEX provided more restriction in ROM and a more significant decrease in MVC grip force than taping at the thumb to restrict UD (Mojaeva, McAlonan and Scott., 2022). The authors of this study suggested that this difference in MVC grip force was due to the proprioceptive inducing properties of rigid tape. The authors further proposed that rigid tape, applied to the dorsum of the wrist, would pull on the skin in response to wrist FLEX prompting the wearer to likely loosen their grip and reduce the exerted force (Mojaeva, McAlonan and Scott. 2022). Taping the wrist in boxers could therefore reduce the requirement to exert MVC grip force. In the current study (Chapter 6), MVC grip force was not assessed. There is therefore uncertainty as to whether different bandaging conditions and wrist positions in boxing could provide a change in MVC grip force. Of importance however, when applying bandaging only or bandaging with tape, technique should be considered. Specifically, the amount of pressure applied as studies performed at the wrist have shown that too much pressure with either bandaging or rigid tape can result in reduced MVC grip force (Takahashi and Demura, 2014; Takahashi et al., 2013).

Minimal percentage of grip force is required to generate significant percentages of wrist stiffness (Holmes, Tat and Kier, 2015). Holmes, Tat and Kier (2015) assessed griping tasks whilst a pneumatic perturbation device delivered a push force causing wrist FLEX or EXT. The authors investigated how gripping modulates forearm muscle co-contraction prior to and during sudden wrist perturbations. From no grip to 10% grip force corresponded to a 36% increase in overall wrist joint stiffness. ECRL and ECRB had the largest stiffness contributions of all the muscles acting at the wrist (Holmes, Tat and Kier, 2015). These muscles, as already discussed, are those where peak force is not affected by taping conditions (Kauranen, Siira, and Vanharanta, 1997). The role of these muscles has already been discussed in counteracting ulnoflexion on impact in boxing (Chapters 2 and 5), providing further evidence of the importance they have in creating sudden wrist joint stiffness. Holmes, Tat and Kier (2015) however observed that while grip force did not change between the baseline and anticipatory time periods during the wrist perturbation task, wrist joint stiffness increased with an increase in muscle co-contraction. The changes observed in the study in boxing (Chapter 6), between the motion on impact and AROM, for bandaging plus tape as compared to bandage only, are therefore likely attributed to muscle stiffness (i.e., active stability) caused by an anticipatory mechanism. This mechanism would be expected with both bandaging plus tape and bandaging only, however likely altered with the former due to a lesser requirement to control the wrist due to an anticipated smaller amount of available motion as compared to bandaging only.

It has been suggested that with repetition, tape can provide biofeedback mediation to alter movement patterns (Morrissey, 2000). If an athlete is exposed to prolonged use of bandaging plus rigid taping in training, and then acutely exposed to competing with bandaging only, this could pose a risk of injury. This risk would unlikely be present if both training and competition used similar bandaging conditions. Care must be taken however as not everyone has similar proprioceptive mechanisms (Long et al., 2017), and therefore responses to taping could vary. In a study, using 24 healthy university students, their proprioceptive discrimination scores for the ankle joint were evaluated and then reassessed after taping (Long et al., 2017). Participants with above average proprioceptive discrimination scores were worse when taped, whereas those with below average scores improved after taping. The authors concluded that taping of the ankle may amplify sensory input in a way that facilitates proprioception for those with low discrimination, however, can produce an input overload that impairs proprioception in those who originally had good levels of discrimination. Understanding the effect of bandaging and taping, beyond the mechanical properties of the materials is therefore warranted.

It is often suggested that prolonged use of tape could decondition a joint. In handball, the effect of wearing an ankle orthosis for four months was evaluated (Jerosch, Thorwesten and Haverkämper, 1998). The results showed that wearing the ankle brace for a period of four months did not lead to a negative effect in jumping capabilities. Boxers, however, typically wear protective equipment at the hand-wrist for several years rather than months, and there could be an actual alteration of proprioception and neuromuscular anticipation towards muscle stiffness. Considering that injuries in boxing still occur, even when rigid tape is applied, it could be beneficial to consider opportunities to use lesser protection during training activities considered as low risk (e.g., bags and pads). This approach could avoid neuromuscular adaptation to one bandaging approach, ensuring risk reduction through exposure to various levels of hand-wrist protection. In competition, significantly less time is spent in this environment than training (Chapter 2), however with increased exposure injury rates. It is therefore important to consider the highest level of protection available at competitive events. Based on the results from the study in Chapter 6, the use of rigid tape is therefore proposed for competition.

7.3 Limitations

In Chapters 4 to 6, various limitations were discussed. Therefore, only the main ones will be considered in this section.

7.3.1 Shot Types

Only the lead arm was chosen for all the studies (Chapters 4 to 6), with two shot types being considered; Jab and Hook. CMC injuries occur with these two shots in the lead arm but not with Uppercut shots, which was therefore omitted for this reason. Further, Uppercut shots are not commonly thrown on bag training equipment, compared to other training activities (e.g., pads and sparring). Various studies conducted in boxing have not opted to assess all six shots available (Liu et al., 2022; Bergün et al., 2017; Cheraghi et al., 2014; Whiting, Gregor and Finerman, 1988), providing more focus on the shots chosen. Some studies have captured all six shots (Piorkowski, Lees and Barton, 2011; Stanley et al., 2018). All these studies in boxing have used motion capture systems requiring direct line of vision, omitting wrist kinematics, which differs from the methodology considered in this programme of research.

7.3.2 Boxing Activity Selected

All the studies (Chapters 4 to 6) were performed solely on bags, which is one type of training method. Whilst a higher incidence of hand-wrist injuries occurs in competition than training, a higher prevalence is recorded in training than competition (Saunders, 2022; Loosemore et al., 2017). The type of injuries in both training and competition are similar, however lesser incidence of injuries at the CMC joints, which are influenced by wrist motion, have been recorded in training as compared to competition (Saunders, 2022). The main difference, anecdotally observed, were the rules on bandaging at certain competitions, with fewer injuries incurred when rigid tape was allowed. The amount of wrist motion recorded on bags in this study, compared to both training and competition at the point when injuries occur, could still differ. However, the study in Chapter 6 observed that wrist motion is significantly reduced on impact when adding tape to bandage compared to bandage only. Currently, there is not identified methodology (Chapter 2), suitable to assess wrist kinematics in more dynamic situations like sparring or competition.

7.4 Future Directions for Research

Considering the results obtained, and the limitations presented in the previous section, further studies should be considered.

7.4.1 Bandaging Techniques and Glove Type, Size, and Brand

In Chapter 6, a standardised technique was used when adding tape to bandage. This used a circular and criss-cross taping technique, with a specific amount of tape used. Identifying which components have the largest effects on wrist motion on impact can allow boxers and practitioners to improve bandaging techniques, possibly using a more cost-effective approach.

In this programme of research, the glove was kept the same to ensure it does not influence the results. Since gloves play an important role in injury reduction, it is recommended to investigate whether type (i.e., Velcro compared to lace fastening), size (i.e., weight in ounces), and brand (i.e., variances within the same brand and between brands), influence wrist motion on impact.

7.4.2 Shot Types, Proximal Kinematic Analysis, and Duration of Activity

In this programme of research, the lead Jab and Hook shots were selected as previously explained (Chapters 2 and 3). Four other shots should be considered in future studies, lead arm Uppercut, and all three shots available in the rear arm. The clinical implications are to identify kinematic variances at the wrist on impact between all shot types, providing additional understanding towards injury prevention and management strategies. Further, it is worth considering the position of the forearm, elbow, and shoulder in relation to the wrist motion on impact to identify if any effects exist. When measuring young healthy individuals, aged between 23 to 30 years old, using a quasi-static methodology, it has been observed that significantly less wrist flexion occurred in supination compared to pronation or neutral forearm positions (Fan et al., 2019). No difference was observed between either pronation or neutral. Conversely, there was no difference for ulnar deviation in all three forearm positions (Fan et al., 2019).

Another consideration is performing a full training boxing round on the bag equipment (i.e., 3-minute round duration), which is a standard duration in both amateur and professional male boxers. Number of rounds should also be considered. The clinical implication is understanding whether the effect of either material deterioration and/or fatigue can influence wrist motion on impact.

7.4.3 Speed of Shot

In this programme of research, submaximal shots were considered to improve the ecological validity of the results obtained (Chapter 3). However, with the knowledge obtained on magnitude on wrist motion on impact, it would be of merit to consider varying the speed of shot within the same shot type, to appreciate if variances occur. In this programme of research, significantly more motion was observed with Jab than Hook shots, with the former generating significantly less average speed compared to the former. Therefore, with higher speeds, less motion was observed. Whether this effect is similar within the same shot would need to be explored.

7.4.4 Experience

Differences between wrist motion magnitude were observed between experience, with increased wrist motion on impact observed with lesser as compared to more experienced boxers. This is supported by findings in more proximal upper limb joints in boxing (Dinu and Louis, 2020). Since experience was not an area considered from the onset of this programme of research, it would be recommended to explore more studies assessing the effect of experience on wrist, and possibly other upper limb joints, in this sport.

7.4.5 Gender

In Chapter 2, it was rationalised why male as compared to female boxers were considered for this programme of research. Fan et al (2019) observed that for wrist motion assessed in female healthy volunteers, using a quasistatic method, wrist FLEX and UD in the non-dominant side were significantly reduced and increased, respectively, in supination compared to pronation forearm positions. No differences were observed for either FLEX or UD in the dominant side. In male healthy volunteers, wrist FLEX was significantly greater in neutral and pronation, compared to supination forearm positions, for both dominant and non-dominant sides (Fan et al., 2019). There were no differences in UD in all three forearm positions and between sides in males (Fan et al., 2019). There appears to be variances in wrist motion between genders, when assessed during quasistatic assessment (Fan et al., 2019). Whether these variances occur at the wrist in more dynamic activities, like boxing, is unsure. Understanding if any differences in wrist motion on impact exist between sides in females, and between genders, can add to a better understanding of both injury prevention and management strategies.

7.4.6 Analysis in Sparring and Competition

It is recommended to consider whether advances in technologies can allow for valid and reliable assessment of wrist motion on impact during more dynamic conditions, like sparring and competition. Currently no equipment has been identified, however, future technologies could likely permit for wrist motion assessment, during these dynamic conditions, ensuring progressing knowledge of wrist kinematics in boxing.

8.0 References

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9.0 Appendices

9.1 Ethics Approvals for the Studies Conducted in Chapter 4 & 5

Subject: Amendments to Study (Ref No: Ref No HWB-S&E-42)

Dear Ian

Title of Research - Accuracy and repeatability of wrist joint angles in Healthy Boxers measured using Polhemus motion tracking system.

Thank you for informing me of the amendment to your study which has been made to incorporate the data into the following proposed research:

To quantify wrist motion during two types of punches; Jab (straight arm) and Hook (bent arm), thrown in boxing.

I am pleased to inform you that the amendment is Approved by the Chair of the Sport & Exercise Research Ethics Group.

Kind regards

Ethics Research Support

Sheffield Hallam University | Faculty of Health and Wellbeing

9.2 Ethics Approval for the Study Conducted in Chapter 6

Subject: Converis - Ethics Review - Amendment Outcome

Dear Ian

Title of Ethics Review: **The Effect of Different Wrapping Techniques on Wrist Angular Excursion on Impact for Jab and Hook Lead Arm Shots in Boxing**
Ethic Review ID: ER40698260
Amendment 1 Title: Risk Assessment format

The amendment to the Ethics Review named above has been reviewed and the outcome is:

Amendment Approved

If you have a query regarding this, please contact your Faculty Ethics Administrator in the first instance.

Kind regards,
Ethics Research Support

9.3 Participant Information Sheet for the Study Conducted in Chapter 4

About the Study

This study titled “Accuracy and repeatability of wrist joint angles in Healthy Boxers measured using Polhemus motion tracking system” is intended to examine the reliability of this system in measuring wrist joint angles. This study will take place at the Physiotherapy department and the Great Britain Boxing Hall at the English Institute of Sport (EIS), Sheffield.

You have volunteered to take part in this study, and your inclusion is dependent on you meeting the set inclusion/exclusion criteria. At no time throughout the study should you be at risk and the SHU Ethics Committee has approved the study method. You are entitled to discuss any parts of this study and are free to withdraw at any time.

What will be required of you?

3 Sensors will be placed on your body; hand, forearm, and arm. A cotton bandage will be wrapped as you would normally do in preparation for a boxing session. You will be standing with your shoulder at 90 degrees, resting your forearm on a wooden stool. A cotton strap will be utilised to secure your forearm to avoid movement at the arm. You will then be asked to repetitively bend your wrist, a total of 12 times (3 times for each available movement). At the end of each movement, you will hold this position for 3 seconds to allow the motion tracking system to record the data in this position. A manual recording will also be taken at the end of each movement using another measuring device (digital inclinometer). This procedure will be performed on your left side only. Your participation will only be required for 15mins for this part of the study.

You will then be asked to perform a brief punching session on a bag in the GB boxing hall. The sensors will again be placed on your body; hand, forearm, and arm. You will be asked to warm-up for 10mins. You will then be asked to hit a gym bag 5 times using a front jab shot, followed by 5 times using a front hook shot. There will be a break of 30seconds between each shot. This procedure will be performed on your left side only. You will be appropriately bandaged and will use an appropriate boxing glove. Your participation will only be required for 15mins for this part of the study.

There will be no disclosure of any information regarding your identity or any other personal information. Your anonymity will be strictly maintained as you will be identified numerically. Your results will be included in the above titled study. Your information will be stored on a secured EIS (English Institute of Sport) server which complies with the EIS security policy guidelines.

If you have any concerns regarding any parts of this study, please contact me directly on the below contact details. Alternatively, please contact Donna Woodhouse (chair of ethics committee).

9.4 Participant Consent Form for the Study Conducted in Chapter 4

TITLE OF RESEARCH STUDY: Accuracy and repeatability of wrist joint angles in Healthy Boxers measured using Polhemus motion tracking system.

Please answer the following questions by ticking the response that applies.

	YES	**NO**
1. I have read the Information Sheet for this study and have had details of the study explained to me.	☐	☐
2. My questions about the study have been answered to my satisfaction and I understand that I may ask further questions at any point.	☐	☐
3. I understand that I am free to withdraw from the study within the time limits outlined in the Information Sheet, without giving a reason for my withdrawal or to decline to answer any questions in the study without any consequences to my future treatment by the researcher.	☐	☐
4. I agree to provide information to the researchers under the conditions of confidentiality set out in the Information Sheet.	☐	☐
5. I wish to participate in the study under the conditions set out in the Information Sheet.	☐	☐
6. I consent to the information collected for the purposes of this research study, once anonymised (so that I cannot be identified), to be used for any other research purposes.	☐	☐

Participant's Signature:_________________________ Date: ___________

Participant's Name (Printed): ______________________________________

Contact details: ____

Researcher's Name (Printed): ______________________________________

Researcher's Signature: ____

Please keep your copy of the consent form and the information sheet together.

9.5 Participant Information Sheet for the Study Conducted in Chapter 6

About the Study

This study titled “The Effect of Different Wrapping Techniques on Wrist Angular Excursion on Impact for Jab and Hook Lead Arm Shots in Boxing” is intended to assess the effect of taping on the amount of wrist joint movement on impact. This study will take place in the Great Britain Boxing Gym located in the English Institute of Sport (EIS), Sheffield.

You have volunteered to take part in this study, and your inclusion is dependent on you meeting the set inclusion/exclusion criteria. At no time throughout the study should you be at risk and the SHU Ethics Committee has approved the study method. You are entitled to discuss any parts of this study and are free to withdraw at any time.

What will be required of you?

3 Sensors will be placed on your body; hand, forearm and arm. A cotton bandage will be wrapped as you would normally do in preparation for a boxing session. You will be seated, resting your forearm on a wooden stool with your elbow at an angle of 70 degrees. A cotton strap will be utilised to secure your forearm to avoid movement at the arm. You will then be asked to repetitively bend your wrist, a total of 12 times (3 times for each available movement). At the end of each movement, you will hold this position for 3 seconds to allow the motion tracking system to record the data in this position.

You will then be asked to perform a brief punching session on a punch bag in the GB boxing hall. You will be asked to warm-up for 10mins. You will then be asked to hit a gym bag 6 times using a front jab shot and 6 times using a front hook shot. There will be a break of 3seconds between each shot. This procedure will be performed on your left side only. A standardised taping technique will be added to the wrapping technique and total of 12 shots will again be conducted. Prior to punching on the bag, you will be asked again to repetitively bend your wrist, a total of 12 times (3 times for each available movement).

In total, 24 shots will be conducted, considerably less shots thrown in any given training session within the specified time. Both order of the shots thrown, and the wrapping techniques will be randomised. The assessor will let you know which order it will be. You will be appropriately bandaged and will use an appropriate boxing glove. Your participation will only be required a total of 45mins for this study. No further follow-ups will be required.

There will be no disclosure of any information regarding your identity or any other personal information. Your anonymity will be strictly maintained as you will be identified numerically. Your results will be included in the above titled study. Your information will be stored on a secured EIS (English Institute of Sport) server which complies with the EIS security policy guidelines.

If you have any concerns regarding any parts of this study, please contact me or my supervisor directly on the below contact details.

9.6 Participant Consent Form for the Study Conducted in Chapter 6

TITLE OF RESEARCH STUDY: The Effect of Different Wrapping Techniques on Wrist Angular Excursion on Impact for Jab and Hook Lead Arm Shots in Boxing

Please answer the following questions by ticking the response that applies.

	YES	**NO**
7. I have read the Information Sheet for this study and have had details of the study explained to me.	☐	☐
8. My questions about the study have been answered to my satisfaction and I understand that I may ask further questions at any point.	☐	☐
9. I understand that I am free to withdraw from the study within the time limits outlined in the Information Sheet, without giving a reason for my withdrawal or to decline to answer any questions in the study without any consequences to my future treatment by the researcher.	☐	☐
10. I agree to provide information to the researchers under the conditions of confidentiality set out in the Information Sheet.	☐	☐
11. I wish to participate in the study under the conditions set out in the Information Sheet.	☐	☐
12. I consent to the information collected for the purposes of this research study, once anonymised (so that I cannot be identified), to be used for any other research purposes.	☐	☐

Participant’s Signature: ______________________________ Date: ___________

Participant’s Name (Printed): ____

Contact details: ____

Researcher’s Name (Printed): ____

Researcher’s Signature: ____

Please keep your copy of the consent form and the information sheet together.

9.7 Normality Tests for the Study Conducted in Chapters 4 and 5

Normality Test for Quasistatic Testing (QS). PI&II (Chapter 4 and 5)

	PI&II_FLEX QS	**PI&II_EXT QS**	**PI&II_UD QS**	**PI&II_RD QS**
N	29	29	29	29
Skewness	0.163	-0.215	0.215	-0.143
Std. error skewness	0.434	0.434	0.434	0.434
Kurtosis	-0.474	-0.209	-0.442	-0.324
Std. error kurtosis	0.845	0.845	0.845	0.845
Shapiro-Wilk W	0.978	0.977	0.976	0.986
Shapiro-Wilk p	0.789	0.767	0.717	0.963

Normality Test for Impact Testing. PI&II (Chapter 4 and 5), J (Jab), H (Hook).

	PI&II_J FLEX	**PI&II_J UD**	**PI&II_H FLEX**	**PI&PII_H UD**
N	29	29	29	29
Skewness	0.0976	-0.0797	0.333	0.154
Std. error skewness	0.434	0.434	0.434	0.434
Kurtosis	-0.639	0.168	-0.342	-0.413
Std. error kurtosis	0.845	0.845	0.845	0.845
Shapiro-Wilk W	0.968	0.976	0.971	0.980
Shapiro-Wilk p	0.519	0.743	0.594	0.841

9.8 Normality Tests for Quasistatic Testing in the Study Conducted in Chapter 6

Normality Test for Quasistatic Testing. PIII (Chapter 6), J (Jab), Free (No Bandage), B (Bandage Only), Tape (Bandage plus Tape).

	PIII_FLEX FREE QS	PIII_EXT FREE QS	PIII_UD FREE QS	PIII_RD FREE QS	PIII_FLEX B QS	PIII_EXT B QS	PIII_UD B QS	PIII_RD B QS	PIII_FLEX TAPE QS	PIII_EXT TAPE QS	PIII_UD TAPE QS	PIII_RD TAPE QS
N	18	18	18	18	18	18	18	18	18	18	18	18
Mean	56.4	72.7	27.8	19.4	29.2	67.5	21.7	15.7	17.2	63.5	17.5	12.8
Skewness	0.0943	0.161	0.176	-0.0135	0.232	0.0329	0.175	0.0645	0.422	0.0741	0.264	-0.0754
Std. error skewness	0.536	0.536	0.536	0.536	0.536	0.536	0.536	0.536	0.536	0.536	0.536	0.536
Kurtosis	-0.684	-0.160	-0.832	0.191	-0.340	-0.577	-0.817	0.0417	-0.222	-0.251	-0.657	0.0314
Std. error kurtosis	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Shapiro-Wilk W	0.975	0.982	0.954	0.941	0.976	0.985	0.954	0.937	0.974	0.990	0.953	0.938
Shapiro-Wilk p	0.884	0.965	0.495	0.302	0.899	0.985	0.491	0.262	0.865	0.899	0.468	0.272

9.9 Normality Tests for Impact Testing in the Study Conducted in Chapter 6

Normality Test for Impact Testing. PIII (Chapter 6), J (Jab), H (Hook), B (Bandage Only), B+T (Bandage plus Tape)

	PIII_J FLEX B	**PIII_J UD B**	**PIII_H FLEX B**	**PIII_H UD B**	**PIII_J FLEX B+T**	**PIII_J UD B+T**	**PIII_H FLEX B+T**	**PIII_H UD B+T**
N	18	18	18	18	18	18	18	18
Mean	18.1	10.8	12.1	8.5	8.3	4.4	5.3	3.0
Skewness	0.309	-0.453	-0.115	-0.141	0.345	-0.491	-0.207	-0.120
Std. error skewness	0.536	0.536	0.536	0.536	0.536	0.536	0.536	0.536
Kurtosis	-0.540	0.118	-0.727	0.233	0.361	-0.148	-0.444	-0.716
Std. error kurtosis	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Shapiro-Wilk W	0.979	0.978	0.968	0.980	0.983	0.969	0.971	0.977
Shapiro-Wilk p	0.939	0.925	0.754	0.955	0.978	0.775	0.809	0.915

9.10 T-Test and Effect Size (d) Analysis for FLEX and UD Motions during Jab and Hook Shots

Motion 1	Motion 2	T-Test	Significance	Effect Size (d)
JAB FLEX	JAB UD	10.3	<0.001	1.9
HOOK FLEX	HOOK UD	8.6	<0.001	1.6
JAB FLEX	HOOK FLEX	9.0	<0.001	1.7
JAB FLEX	HOOK UD	8.4	<0.001	1.6

9.11 ANOVAs for Shot Types and Bandaging Technique on Wrist Motion (degrees) during Impact Testing

			Sum of Squares	df	Mean Square	F	p	η^2
IMPACT TESTING	Wrist Motion (FLEX)	Shot Types	589.4	1	589.4	76.8	<0.001	0.28
		Residual	130.5	17	7.7			
		Bandaging Techniques	1207	1	1207	2376.5	<0.001	0.58
		Residual	8.1	17	0.5			
		Shot Types * Bandaging Techniques	54.1	1	54.1	94	<0.001	0.03
		Residual	9.8	17	0.6			
	Wrist Motion (UD)	Shot Types	154	1	154	111	<0.001	0.165
		Residual	23.6	17	1.4			
		Bandaging Techniques	679	1	679	968.6	<0.001	0.729
		Residual	11.9	17	0.7			
		Shot Types * Bandaging Techniques	8.5	1	8.5	21.2	<0.001	0.009
		Residual	6.8	17	0.4			

9.12 ANOVAs for Shot Types and Bandaging Technique on Time to Peak Wrist Angle (secs) and Average Speed of Shot (m/s) during Impact Testing.

			Sum of Squares	df	Mean Square	F	p	η^2
IMPACT TESTING	Time to Peak Wrist Angle	Shot Types	0.002	1	0.002	19.8	<.001***	0.170***
		Residual	0.001	17	8.66E-05			
		Bandaging Techniques	0.003	1	0.013	76.6	<.001***	0.267***
		Residual	5.94E-04	17	3.49E-05			
		Shot Types * Bandaging Techniques	7.81E-05	1	7.81E-05	2.3	0.146	0.008
		Residual	5.72E-04	17	3.36E-05			
	Average Speed of Shot	Shot Types	65.3	1	65.4	64.2	<0.001***	0.365***
		Residual	17.3	17	1			
		Bandaging Techniques	3.5	1	3.5	16.3	<0.001***	0.019
		Residual	3.6	17	0.2			
		Shot Types * Bandaging Techniques	0	1	0	0.1	0.801	0.001
		Residual	3.6	17	0.2			

9.13 ANOVAs for Bandaging Techniques on Wrist Motion (Degrees) during Quasistatic Testing.

			Sum of Squares	df	Mean Square	F	p	η²
Wrist Motion on Quasistatic Testing	FLEX	Bandaging Techniques	14514	2	7257	145	<0.001	0.850
		Residual	2558	51	50.2			
	EXT	Bandaging Techniques	773	2	386.6	5	0.011	0.163
		Residual	3974	51	77.9			
	UD	Bandaging Techniques	969	2	484.4	16	<0.001	0.386
		Residual	1540	51	30.2			
	RD	Bandaging Techniques	393	2	196	6.8	0.002	0.210
		Residual	1481	51	29			