THE EFFECTS OF HARD AND SOFT RIB PROTECTOR GARMENTS ON THROW PERFORMANCE AND LOWER TRUNK KINEMATICS OF QUARTERBACKS DURING OVERHAND FOOTBALL PASSING AND FLEXIBILITY TASKS

by

Marika Ayana Walker

(Under the Direction of Kathy Jean Simpson)

ABSTRACT

Rib protectors may help reduce rib injuries to American football quarterbacks, but players may not wear them if perceived to or actually do hinder athletic performance and trunk mobility. The best method for assessing rib protectors' influence on maximal trunk mobility is unclear. For sub-study #1, the purposes were to determine if hardness of two rib protector garments affected lower-thoracic axial-rotation kinematics, performance, and athletes' perceptions; and whether perceptions improved after performing a football throwing task. For sub-study #2, the purposes were to determine which flexibility type (active-assisted, maximal speed, self-selected speed) demonstrated the highest flexibility values for trunk lateral flexion and axial rotation, and if rib protectors affect trunk flexibility. Twelve male quarterbacks completed rib protector perception scales before and after ten maximal effort-accuracy throws and flexibility tasks in two directions (lateral flexion, axial rotation) for each rib protector condition: soft-rib, hard-rib, and control (compression shirt). Axial-rotation kinematics, performance measures, and perception scores of each rib protector were compared to control using non-inferiority testing (group and within individual comparisons) for throwing. Neither rib protector was inferior to control for axial kinematics or performance, but hard rib mobility was perceived to be inferior before and after throwing. Though 11/12 individuals had inconclusive results for most measures (117/168 individual non-inferiority tests), the remaining rib protector outcomes for individuals varied. Outcomes of the rib protector x flexibility protocol repeated measures analysis of variances ($n = 11$) and Fisher's LSD posthoc tests demonstrated that, for both rib protectors, the protocol displaying the highest flexibility value for lateral flexion was the self-selected speed and for axial rotation, maximal speed and active-assisted. Subsequent non-inferiority testing of the rib protectors showed that neither rib protector was inferior to control for lateral flexion, but axial rotation was inconclusive. Both sub-studies showed that both rib protectors can be recommended, as neither appeared to hinder quarterbacks' performance, lumbo-thoracic kinematics, or lumbo-thoracic mobility. Therefore, individuals should choose the rib protector best for them.

INDEX WORDS: Spinal mobility, Throwing speed, Throwing accuracy, Non-inferiority testing, Range of motion, Active-assisted

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by

MARIKA AYANA WALKER

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MARIKA AYANA WALKER

Major Professor: Kathy Jean Simpson

Committee: Cathy Brown- Crowell
Timothy Foutz

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
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DEDICATION

This work is dedicated, first and foremost, to God. Without Him, none of my achievements would exist. This is also dedicated to my Mom and my brother who have gotten me through my most difficult times during this process. Mommy you have always been my number one supporter and I would not be the woman I am today without you showing what it is to be confident, resilient, and selfless. And David, you have been my research and business consultant, and most importantly, my spiritual advisor. God knew that I would need you to be successful in this program so he had you go through all of the hardships first!! ☺ I love you both very much.

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CHAPTER 1: Introduction

During an American football game at the professional level, an offensive player may be hit by an approaching defensive player, with momenta of up to 1,215 kg · m/s[1]. Depending on the location of the impact, these hits can cause injuries with acute (ranging from mild to fatal) and/or long-term effects due to the cumulative nature of repetitive impact[2,3].

The torso may now be subject to more impact collisions than before, as recent rule changes meant to protect the head and legs may put the ribs/abdominal area at greater risk. In an effort to reduce the risk of long-term effects from chronic traumatic encephalopathy (CTE)[4] due to repeated head impacts, in 2010 the National Football League (NFL) implemented rule changes that prohibited defensive players from tackling helmet first above the shoulders of players in a 'defenseless' position (i.e., unprepared to protect oneself from a hit)[5]. In addition, defensive players cannot block below the waist. This leaves the torso where tackles and blocks are always allowed.

Possibly as a result of the rule changes, the number of injuries to the spine and axial skeleton in the NFL has increased from an average of 197 per year during the 2000-2010 seasons to 235 per year for the 2012-2013 seasons[6,7]. Specifically, for the ribs, the number increased from 86 total rib injuries over the entire 11 year period to 97 rib injuries over the 2 year period[6,7].

Moreover, players who experience high-speed impacts to the trunk area sustain injuries that can range in severity, from relatively minor, such as rib and pulmonary contusions, to moderately serious rib fractures and costal cartilage ruptures, up to fatal solid organ injury[7–10]. For the most common and minor injuries to the thoracic/abdominal region, contusions are often painful[11,12]. Moreover, contusions were the most common injury for all football injuries reported by an epidemiology study conducted in NFL training camps from 1998 to 2007[9]. However, how many of these contusions occurred to the lower portion of the trunk is unknown, as specific contusion location was not reported. Among the moderately serious injuries, acute rib fracture may occur[13,14]. Of all axial skeleton or spine injuries occurring to NFL players, almost 3.9% occurred to the thoracic spine and the ribs over the course of 11 seasons between 2000 to 2010 and 11.6% of those were fractures[7] . The mean number of days lost due to rib fracture was approximately 17 days during that time frame. In addition to rib fractures, costal cartilage injuries occur in about one player per team per year in the NFL and may require the athlete to sit out for up to 4 weeks[10]. For the most serious injury level, solid organ injury can occur independently and, additionally, when lower rib fracture due to blunt trauma occurs, there is always a risk of solid organ injury following[15,16]. Though uncommon, when blunt abdominal injuries, especially to the spleen, occur during contact sports there are often very serious, if not fatal consequences[17]. The spleen is the most commonly injured solid organ in sports and is also the most common cause of death due to abdominal trauma in athletes[17]. Serious kidney injuries often do not result in death, but occurred on average 2.7 times per season in the NFL between 1986 and 2004[18].

Rib and abdominal region protectors could prevent or reduce the severity of aforementioned injuries if more widely used [15,16]. Historically, rib protection garments have been used, when appropriate, to allow the athlete to return to play after an abdominal or a rib injury [10,13]. Additionally, product marketing for rib (and abdominal) protection in football has increased with various companies claiming their usefulness in preventing/reducing future injury. Still, it may be some time before there is sufficient epidemiological evidence to prove the efficacy of rib protectors for reducing the risk of serious injury to the abdominal area.

To date, there are no data to show how often athletes wear rib protectors. There are many prophylactic devices, such as ankle braces, headgear, and mouth guards proven to prevent injury, but athletes often do not wear them based on lack of comfort or perceived and/or actual decreased performance[19–21]. As with those devices, efficacy of rib protectors will not matter much if the athletes do not wear them. According to equipment managers at one NCAA Division I college (personal communication), among offensive collegiate football players most likely to be hit or injured, only an estimated 20% of them voluntarily wear rib protectors. Rib protectors are not mandatory gear, and, therefore, if rib protectors are perceived to hinder athletic performance (e.g. quickness, speed, agility, mobility), athletes won't wear them. As most abdominal and rib injuries are not as common as injuries to other body regions, administrators, coaches and athletes often must be convinced that the benefits of such equipment outweigh any possible negative effects it may have on performance to increase compliance. Though sportswear companies are increasing marketing of rib protectors and, as a result, are seeing an increase in sales[22], evidence that the rib protectors will not inhibit movement and performance is vital for those who may be skeptical. If athletes perceive these rib protectors to have negative effects, it is important to know what characteristics of the padding (e.g. compression, rigidity, bulkiness) may contribute to that and if they translate to detriments in performance factors.

Two major types of rib protection (Figure 1.1) with vastly different characteristics are currently available: the ‘traditional’ type and the ‘garment’ type. The ‘traditional’ type has thick padding covered by hard plastic in some areas and attaches to a player’s shoulder pads and/or has shoulder straps. The ‘garment’ type of rib protection involves two or more thick pieces of foam padding (soft-rib) or two hard, protective plates (hard-rib) in the lower rib and/or spinal area that is embedded into a knit compression shirt worn underneath other mandatory football pads. As the garment form of rib protection often weighs less and is not as thick as the traditional form, it may be a more appealing choice among football players that aren’t already open to wearing the ‘traditional’ form of rib protection for injury prevention purposes. Additionally, informal impact testing (Appendix E) has shown that both garments can reduce the peak impact force and the max rate of application experienced with a compression shirt alone by about half indicating they may still be effective in reducing injury with their reduced bulkiness.

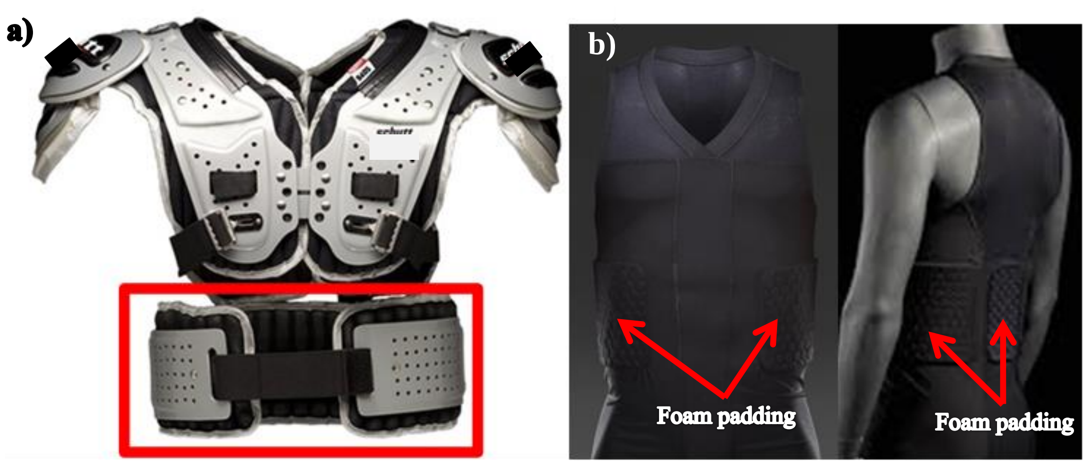

Figure 1.1— Two major types of rib protectors. (a) The ‘traditional’ type (surrounded by the red box) is usually attached to the shoulder pads. (b) The ‘garment’ type consists of a compression shirt with padding in the rib area.

Two variations of the 'garment' type of rib protector, shown in Figure 1.2, were included in this study, as this type is less likely to hinder performance and is a more likely choice for players who are skeptical of wearing rib protection. The soft-rib protector consisted of a sleeveless compression garment with individual honeycomb-shaped pieces of soft foam padding sewn into both rib areas and the lower spine area. The hard-rib protector also consisted of a sleeveless compression garment but contained hard moldable (with hot water) inserts on both side of the ribs. The side of the insert worn against the ribs consisted of stiff foam while the outside of the insert consisted of hard plastic with honeycomb shaped negative space. In addition, two flexible foam pieces were sewn into the garment over the sternum and lower spine areas. The rib protectors chosen provided two very diverse versions of rib protector garments as their characteristics (compression, rigidity, bulkiness) may affect mobility and performance differently. For the control condition, the same compression garment for the hard-rib condition was worn without the inserts in order to provide a condition where the only difference was the lack of protection in the rib area. Compression shirts or other t-shirts are often worn underneath football pads in game settings to wick moisture and heat away from the body, and to keep the pads in place once the athlete begins to perspire[23,24]. Therefore, using a compression shirt as a control condition was appropriate in this study. Both compression shirts of this study were shown to have a 7.6% difference in stiffness at the garment level when fully assembled with the rib protectors in them (soft-rib: 227.57 N/m, hard-rib: 246.35 N/m), as shown in Appendix F. The materials used in the shirts, though, had differing values for Young's modulus (**soft-rib** mesh: 1.000 x 10^{-4} GPa, solid: 2.401 x 10^{-4} GPa; **hard-rib** mesh: 7.026 x 10^{-4} GPa, solid: 4.878 x 10^{-4} GPa) (Appendix G).

Rib Protector		Structure Description	Thickness
soft-rib		• Soft padding • Honeycomb structure • Individual pieces	**75% Solid:** .64 mm **25% Mesh:** .27 mm
hard-rib		• Hard plate insert (foam outside layer and protective plastic outside layer) • Smooth, continuous structure • Moldable	**40% Solid:** .41 mm **60% Mesh:** .46 mm

Figure 1.2 — The rib protectors to be included in this study and corresponding descriptions. All logos were covered to avoid performer bias due to company brand. The control condition consisted of the hard-rib compression shirt without the plastic inserts.

Quarterbacks could benefit from rib protectors because they are susceptible to injury and are crucial to team success in football games and must remain uninjured. Skill position players (those most directly responsible for scoring or preventing points in a game), particularly quarterbacks, are at a high risk of getting hit by defensive players since they are the first to receive the ball when a play begins. Because they tend to be thinner than linemen and linebackers their rib area is often more susceptible to injury than those other positions[25]. In addition, they must stand in an upright position as they are preparing to throw, exposing the rib and lower abdominal area. Quarterbacks are not required to wear rib protection but may do so voluntarily. Though they could benefit greatly from additional protective gear, they often require more mobility in the frontal and axial planes, namely while completing an overhand football pass, than most other positions[26,27].

There are many common movements that quarterbacks must complete quickly and accurately. Of those movements, throwing seems to be the task that has the most amount of trunk movement. Pelvis and trunk rotation are essential in ensuring that the throw will be the most effective[28,29]. In addition, a study by Roach et al. has shown that wearing a rigid, full-torso brace can slightly reduce throwing speed of baseball players[27]. However, football throwing has slightly different trunk kinematics than baseball pitching[29]. Still, if trunk movement and performance are affected by rib protectors, it would likely be during this task.

It is important to understand the effect of rib protectors on torso axial rotation, as the majority of football passes are within 10 yards. However, the amount of axial trunk rotation required for these short passes likely is less than rotation needed for much longer passes. In longer passes restriction of the trunk could lead to missing the receiver due to releasing the ball in an incorrect direction, release point, and/or insufficient ball speed. As only a limited throw distance was feasible for testing in our lab setting, it also was valuable to see if rib protectors restrict trunk range of motion (ROM) during maximum flexibility tasks. Although not as functional as throwing, the flexibility tasks should produce maximum trunk mobility. I believed that any kinematic differences among rib protectors would be detectable using the football pass and flexibility tasks.

Flexibility protocols can vary in several different ways, including movement speed or type of motion (active vs passive). These differences can affect which somatosensory reflexes are activated in the muscles and ligaments[30].

Maximum speed flexibility protocols may be more generalizable to actual throwing, but they may not necessarily reach the maximum ROM that may be experienced in other movements. Although active ROM is more relevant to what occurs when throwing a football than passive ROM, passive ROM usually produces greater flexibility values. Therefore, it was important to explore different dynamic trunk rotation tasks to determine which protocol evoked the maximal ROM values for trunk range of motion.

At present, there is no evidence indicating whether or not rib protectors influence performance or factors related to performance, such as trunk mobility, accuracy, and speed. If the outcomes of this study show that rib protectors have no negative effect on performance and trunk mobility, this evidence could encourage skeptical coaches and athletes to use this form of rib protection to reduce the risk of serious injury and provide sports medicine clinicians with data to make recommendations. If the outcomes demonstrate detrimental effects, then results could promote the need for improved designs by manufacturers. Therefore, the question of interest was: How do hard and soft rib protector garments affect the performance and axial trunk mobility of quarterbacks during throwing as well as their axial and lateral flexion trunk flexibility?

Purpose of the overall study

The **purpose of the overall study** was to determine how wearing two different rib/abdominal football protectors affect trunk kinematics, task speed, and task accuracy during a throwing task (**sub-study 1**), and trunk range of motion during three trunk flexibility tasks (**sub-study 2**), of former or current quarterbacks with experience in overhand football passing.

Specific aims of this study were as follows:

1) Determine the effects of two rib protectors on performance measures, trunk kinematics, and perceptions during an overhand football throw, including:

    a) axial lower-trunk kinematics,

    b) time to complete the throwing task,

    c) ball speed and throwing accuracy, and

    d) perceptions of performance and mobility before and after completing throws.

2) Determine the effects of three rib protector garments on frontal and transverse plane lower-trunk range of motion (ROM) using the flexibility protocol that demonstrated the highest ROM among the following combinations of trunk flexibility types and movement speed protocols: active at a self-selected speed (SS), active-assisted at a self-selected speed (AA), and maximal speed (MS).

Predictions, Rationales, and Hypotheses

In general, for any rib protector (soft-rib, hard-rib) compared to the control condition (control) of not wearing a rib protector (compression shirt only), it was expected that the rib protectors would not perform inferiorly to the control (non-inferiority). It was expected that there would be high inter-participant variability because some individuals would have different results than others as usually happens with sports equipment[31–35]. This implies that there may be different optima of equipment design for different people. Therefore individual non-inferiority testing was conducted for the overhand football throwing sub-study to determine the effects of rib protectors on each participant.

For each sub-study, the general predictions and rationales are presented first. The corresponding hypotheses then follow.

1) Sub-study #1: Overhand Football Throwing:

Definitions:

Lower-trunk axial angle (LT-AX): The angle of the T8 vertebra relative to the L3 vertebra representing rotation about the longitudinal axis.

Peak axial relative trunk displacement (peak AX disp): The difference between maximum axial rotation angle of LT-AX towards the target and maximum axial rotation of LT-AX away from the throwing target.

Peak forward axial relative trunk angular velocity (peak AX vel): maximum axial angular velocity of LT-AX towards the target.

Peak forward axial relative trunk angular acceleration (peak AX accel): maximum axial angular acceleration of LT-AX towards the target.

Pelvic acceleration phase: throwing phase beginning at touchdown of the back foot on the force plate and ending at ball release

Non-inferiority: outcome of a rib protector is not inferior to that of the control (i.e., outcome is either equivalent or superior to the control outcome).

Difference score: rib protector's outcome minus the control's outcome.

Predictions and Rationales

Whether a rib protector is present or not, maximal torque must be produced by the muscles in the trunk in the direction of axial rotation in order to perform a maximal effort throw. Most players wear a compression shirt similar to the compression shirt of a garment-style rib protector. The compression shirt alone is surmised to generate some small, but negligible, amount of mechanical restriction during axial rotation. When the full garment-style rib protector is worn, there likely is increased mechanical resistance, and hence, a greater reaction torque due to: a) greater stretch of the knit from the thickness of the rib protector padding in the garment, and b) stiffness of the rib protection materials. Therefore, all else equal, when wearing the full rib protector, there would be less axial net resultant torque acting on the lower trunk (Figure 1.3).

Consequently, by Newton's second law, this would result in proportionately decreased axial acceleration of the lower trunk. This would lead to several consequences. First, decreased axial rotation would cause lower peak magnitudes of AX disp, peak AX vel, and peak AX accel. Second, lower resultant torque also combined with less AX displacement would lead to decreased total angular work. Third, there would be longer time to peak AX accel and throw time due to lower axial accelerations. Fourth, for the rib protector conditions compared to control, there would be lower throw error, as the individual's trunk would be rotating slower and would allow more time for the athlete to react and release the ball during the throw.

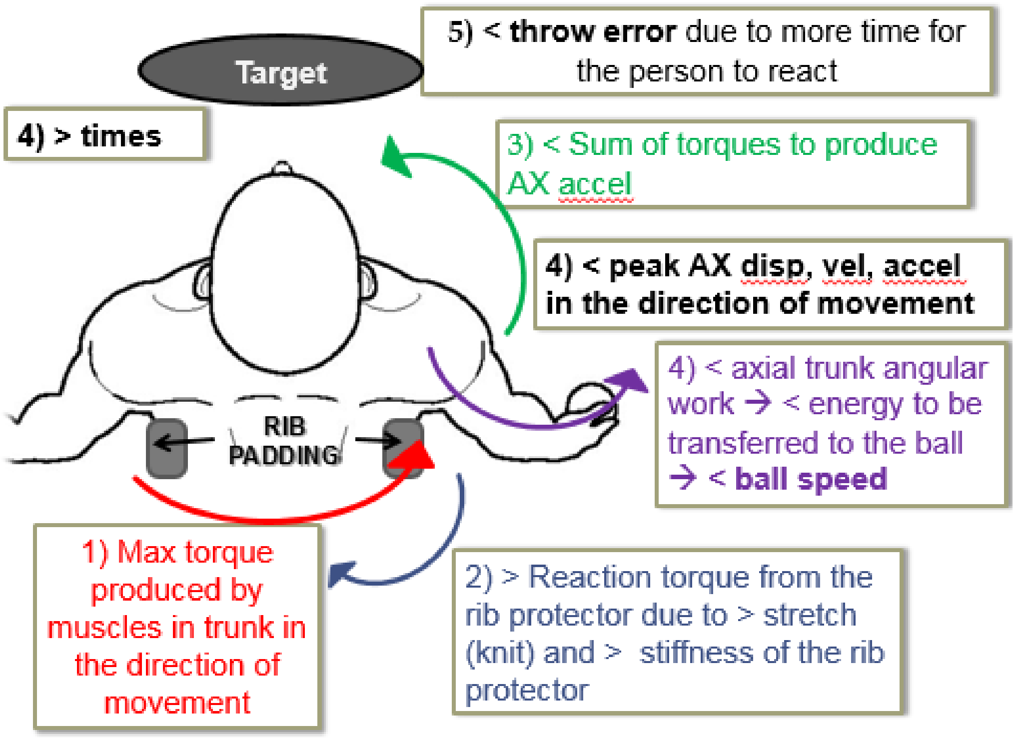

Figure 1.3 — Summary of the rationales for predictions of trunk kinematic and throw performance-outcomes. The effect of wearing rib protection (rib padding) is shown step-by-step. Variables being analyzed are in bold. Though these differences are predicted, they will not be behaviorally significant. AX = axial; disp = displacement; vel = velocity; accel = acceleration.

Comparing the rib-protectors, the hard-rib protector should have greater stiffness, thus would produce greater mechanical restriction to axial rotation than the soft-rib, so the previously explained effects would be slightly greater. However, for both rib protectors, because the axial displacement of the trunk would not be high enough to significantly deform the rib protectors, the mechanical restriction and its effects on net torque was not anticipated to cause any behaviorally meaningful differences for any of the previously mentioned variables.

For this study, it should be noted that because angular acceleration is directly proportional to net torque, acceleration is the measure by which the consequences of mechanical restriction can be indirectly assessed, not net torque. Deriving valid lower-trunk axial torques for conditions when rib protector garments are worn is not feasible. However, testing of stiffness properties of the rib protector garments and control shirt was also performed aposteriori to help determine whether mechanical restriction potentially influenced kinematic and performance outcomes.

Trunk Kinematics Hypotheses

For the pelvic acceleration phase of the maximal effort and accuracy football throwing task each rib protector condition (soft-rib, hard-rib) compared to control using the difference score would be non-inferior for the following kinematic variables:

1) peak AX disp,
2) peak AX vel,
3) peak AX accel, and
4) time to peak AX accel.

Throw Performance Hypotheses

For the maximal effort and accuracy football throwing task, each rib protector would be non-inferior to control for the following performance variables:

1) throw time,
2) ball speed,
3) throw error.

2) Sub-study #2: Trunk Flexibility:

Definitions:

Active-assisted protocol: partially passive protocol; at the ends of the active range of motion of a dynamic flexibility task, the participant grabbed an object to rotate the trunk a little further.

Predictions and Rationales

In order to cause lateral flexion of the spine the lumbar erector spinae, the intertransversarii, and the interspinales muscles on the contralateral side as well as the quadratus lumborum on the side of the bend and the abdominals would have to contract[36]. For rotation, the multifidus muscles in the lumbar region on the side of the direction of rotation would contract while the longissimus and iliocostalis muscles on the other side were also active. In addition, the internal oblique on the side of rotation and the external oblique on the opposite side would both also be active during rotation. When muscles contract, they often cause activation of the muscle spindles causing a stretch reflex to resist change in length of the muscles[30]. These muscle spindles can be activated either due to high rates of stretch or high magnitudes of stretch. Golgi tendon organs behave similarly at higher muscle forces. As a result, activation of either of these somatosensory receptors would limit the ROM. During passive stretching, the muscle would be less stiff[37] and the magnitude of muscle force necessary to activate a tendon organ would be higher than during active stretching[30]. Therefore, since the active-assisted protocol is partly passive, it would allow a greater range of motion before these receptors are activated.

Maximal speed causes the Golgi tendon organs to react more rapidly than they would at a slower rate of rotation. In addition, the viscoelasticity of the muscle and connective tissue causes them to be stiffer at higher rates of applied load. Therefore, the increased muscle tone (causing early activation of the muscle spindles and tendon organs) caused by the magnitude of muscle contraction necessary to accelerate the trunk, as well as the rate it is applied, would cause the tissues to have less stretch with higher amounts of load. This would outweigh the additional range of motion that the momentum of the movement would cause. The purely active protocol at the self-selected speed would allow the muscles to stretch at a rate that does not greatly increase stiffness and would also avoid activating the sensory organs to early. However, the purely active rotation of the muscles alone would not be able to rotate the trunk as much as an active-assisted protocol could.

As explained for throwing, the forces that the trunk muscles produce would have been contributed to overcoming the shear forces caused by the padding of the rib protection. In addition, increased bending forces would have had to be produced by the muscles of the trunk to overcome the stiff padding that was present in the rib protector condition, causing decreased lateral flexion. Since the displacement (that the muscles would have had to rotate the trunk to) would be much greater, the amount of shear stress would be greater and harder to overcome. As the hard-rib condition is more rigid, it would require enough torque to make it behaviorally different and inferior to the control but since the soft-rib has individual pieces and is not as stiff, it would be non-inferior to the control.

Hypotheses

a) Due to the previously explained mechanisms, we hypothesized that the largest mean trunk ROM values in both directions (axial and anteroposterior) would be seen with the active-assisted protocol (AA), followed by the self-selected speed protocol (SS), and finally the maximal speed protocol (MS).

b) Compared to CON, the rib protector conditions (soft-rib, hard-rib) for the chosen of three semi-functional flexibility tasks (SS, AA, MS), the soft-rib would be non-inferior and the hard-rib would be inferior for relative angular displacement between the T8 and L3 vertebrae about the axial (AX trunk displacement) and anteroposterior (AP trunk displacement) axes.

CHAPTER 2:Review of Literature

In this chapter, first, the prevalence of injuries that occur in the rib/abdominal area will be reported to establish the importance of rib protector garments and to illuminate the rationales behind this study. The existing types of rib protectors, as well as their protective materials and structures, will then be presented. Afterward, the trunk anatomy (vertebrae, muscles, and connective tissue) will be described in order to understand the mechanism of injury occurring in the rib/abdominal area. Trunk range of motion will also be discussed to establish ranges to be expected when looking at any movement. The flexibility protocols traditionally used to establish trunk ranges of motion will then be reviewed to establish a rationales for the methodology used in the trunk flexibility sub-study (2). To justify the selection of the movement being analyzed in sub-study 1, the overhand throw, specifically football passing, will be examined. Particularly, its phases and purposes in American football and how the trunk anatomy is involved during these movements will be explained to understand how they may be affected by a rib protector garment. Finally, previously developed methodologies for measuring throwing performance will be reviewed to explain the rationales behind the specific methodology being used in the overhand football throwing sub-study.

Importance of Football Rib Protectors

In this section the prevalence of rib/abdominal football injuries and the mechanism in which they occur will be reviewed in order to understand why football rib protectors are important.

Prevalence of Rib/Abdominal Football Injuries

In the lower rib/abdominal area there are multiple injuries that can occur including: contusions, solid organ injury (SOI), and rib fracture (including chondral) due to blunt trauma[7–11,17]. Of these, contusions anywhere in the body are the most common, accounting for 19% of game injuries, according to researchers of an epidemiological study conducted in the National Football League (NFL) from 1998 to 2007[8]. Bony contusions as well as pulmonary contusions, specifically, may occur due to impact. However, the number of pulmonary contusions is unknown because it is rarely reported in literature; likely because these injuries may be missed in the athletic setting due to the lack of pathognomonic signs or symptoms[12]. As pulmonary contusions are shown to be largely predicted by the number of fractured ribs that a person sustains,[15] a decrease in rib fractures could lead to a decrease in pulmonary contusions.

Rib fractures are relatively common in American football. According to a study by Mall et al., 3.9% of spine and axial skeleton injuries in the NFL occur to the thoracic spine and ribs, with even greater percentages occurring to football player positions at risk of getting tackled: quarterbacks (9.3%), wide receivers (8.1%), and running backs (7.0%)[7]. In addition, on average, team physicians of NFL teams have reported approximately one costal cartilage injury per team per year[10]. However, chondral rib injuries are known to be much more prevalent than what has been previously reported[10]. Though rib injuries alone are not fatal, there is reportedly and average of 17 days lost due to rib fracture and can take as much as 4 weeks to heal sufficiently before the athlete can return to play[7,10]. Rib fracture is the most common serious injury of the chest wall in the general population and may likely increase prevalence in those who are at most risk of suffering concussive blows to the chest[38].

In the event that rib fracture, particularly to the lower left side, does occur, there is a chance that death due to solid organ injury(SOI) of the spleen may also occur[16,17]. The spleen is the most commonly injured abdominal organ and most common cause of death due to abdominal trauma in sports[16,17]. Particularly, location, severity, and mechanism of lower rib fractures are all associated with the type of SOI that may likely occur[15]. Rib protection is often recommended when an athlete with a splenic injury is returning to play and therefore may be useful for preventative purposes[39]. Lower rib fractures on the right most often lead to liver injury[16]. Finally, according to Brophy et al., an average of 2.7 renal injuries per year was reported in the NFL from 1986 to 2004, commonly due to blunt trauma in the rib area[18].

Current Use of Rib Protectors

Rib protection, particularly by wearing a rib protector garment, has been reportedly used for return to play after a rib/abdominal injury for chondral rib fractures, rib contusions, and splenic injuries[10,39,40]. In addition, according to two collegiate football equipment managers (personal communication), "traditional" rib protectors are often used by defensive players. Traditional rib protectors are thick and therefore are not well received by most players[10]. Though no research has reported prevalence of use for football rib protectors, in a case study McAdams et al. stated that no complaints were reported from athletes who were made to wear a rib protection garment after a rib injury[10]. The popularity of rib protection garments has increased, partly due to more aggressive marketing from the companies that sell them and increased sales to elite athletes[22]. Yet, the belief is that they are still not commonly used by offensive players. However, there are limited data tracking usage to confirm this perception.

Materials

Rib protection usually consists of one of three designs: a rigid outer shell with foam padding, a rigid shell alone, or foam padding alone[41]. The rigid outer shell serves to decrease the pressure on the player's tissues by spreading the impact load being applied over a larger surface area of the body. This is usually achieved through a curvature in the shell that will fit the contour of the person's trunk, but will also increase surface area and allow large gross deformation. In addition to the deformation occurring in the outer shell, there is also compressive deformation of the foam padding. The padding theoretically compresses to increase the contact time which decreases the amount of force at impact, which also increases energy absorption[41].

The materials that may be used for impact protection are fiber composites such as polymer matrix composites (PMC), foams, or porous materials[42]. PMCs are able to combine the strength and high elastic modulus of a high performance fiber with the energy absorption properties of a polymeric matrix[42]. Finally, porous materials allow for absorption of impact due to compression of the air spaces as well as the energy absorption properties of the air in those spaces. For this reason, a porous material would likely absorb just as much energy as its solid counterpart but with less material being used which could save money for companies producing them and lead to more lightweight materials that are less taxing on the body[42].

The shell material used in sports protective equipment usually consists of polymeric plastics such as polycarbonate or polyethylene[43]. Polycarbonate is a very rigid material that will fracture under extremely high impacts while polyethylene is somewhat flexible and therefore is at less risk of fracturing[43]. However, polyethylene shells must be reinforced geometrically to allow enough stiffness to avoid permanent damage of the shell or bottoming out before the impact is sufficiently absorbed[41,43].

The foam padding is often made from expanded polyurethane, polystyrene, polypropylene, or syntactic epoxy[44]. These materials allow the energy at impact to be dissipated during the stress plateau. Sometimes multiple layers of foams are used to utilize the positive properties of many functionally graded materials[44].

Structure

Besides constructing foams from existing polymers and adding air pockets to make porous materials, polymeric materials are often structured into sandwich or lattice systems for protective equipment[42]. According to Qiao et al., this allows the equipment to maintain a low density core and attain high energy absorption through compression of the structure, all while utilizing the favorable mechanical properties of the material being used, e.g. high resistance to bending and high load capacity at a low weight. With a honeycomb sandwich structure, the impact is absorbed through crushing of the core. Similarly, with a lattice or truss structure, Qiao states that the impact is absorbed through buckling of the core struts.

Functional Trunk Anatomy

The Vertebral Column

Several structures within the trunk contribute to its stability and generation of movement. The vertebral column as a whole also provides support and flexibility to the trunk as well as protects the spinal cord. The vertebral column consists of 33 vertebrae, 24 of which contribute to movement,[36] and several supporting structures. The three moveable segments are the cervical, thoracic, and lumbar regions, including seven cervical, twelve thoracic, and five thoracic vertebrae, respectively.

The anterior side of the moveable portion of the vertebral column, contains vertebral bodies with intervertebral discs between them[36]. The annulus fibers within the intervertebral disks allow for compression and tension at either end of the vertebrae during flexion, extension, and lateral bending. During axial rotation of the trunk, there is both tension and shear forces within the annulus fibrosus of the disk. Since half of the fibers are oriented in one direction of rotation and the other half are oriented in the other direction, the fibers in the direction of rotation become taut while the other fibers slacken[36]. This causes a shear force across the plane of rotation. The nucleus pulposus, located at the inner core of the intervertebral disk, is comprised of mostly water (80-90%) and loose collagen fibers that form a jelly-like substance. This structure does not contribute to or affect intervertebral movements in healthy populations but allows the vertebral disk to withstand high amounts of compression[36].

In addition to the disks, there are also longitudinal ligaments that run down the entire length of the spine on the anterior and posterior sides[36]. These passive tissues are stressed when there is spinal movement in any direction[45]. The longitudinal ligaments of the anterior portion, as well as the posterior portion, restrict the trunk from having excessive flexion or extension[45]. The anterior longitudinal ligament limits hyperextension and restrains relative anterior shear motion between two adjacent vertebrae[36].

Within the posterior portion of the moveable vertebral segments there are transverse and spinous processes, neural arches, intervertebral joints, and more ligaments[36].The transverse processes protrude from either side of the neural arch. The spinous, transverse, inferior articular, and superior articular processes protrude from posterior end of the vertebrae dorsally, medially and laterally, inferiorly, and superiorly, respectively. The bones of the laminae and the pedicles within the neural arches have high tensile strength. Particularly, the spinous and transverse processes are the attachment sites for the muscles and ligaments within the spine. The inferior articular facets and the superior articular facet form joints that prevent forward displacement of the vertebrae. In addition, the bones of the apophyseal joints bear significant amounts of load during hyperextension, flexion, and rotation.

For connective tissue, the ligamentum flavum, running longitudinally up the posterior side of the vertebral column, is very elastic, allowing it to elongate with flexion of the trunk and contract with extension and return to its original length. It is always in constant tension while the spine is in a neutral position. However, it has an extremely long toe-region, meaning that it can sustain a pretty large amount of strain without much stress through 'un-crimping' of the collagen fibers. The supraspinous and interspinous ligaments also run longitudinally and resist shear and forward bending of the spine. The bilateral intertransverse ligaments resist excessive lateral bending and run along the transverse processes on each side of the spinal column.

The first ten ribs within the thoracic cavity are connected by costal cartilage via the costochondral junction which does not have any movement[13]. There are four additional ligaments that attach the ribs (including the 11th and 12th) to the vertebral body and transverse processes[36]. They do not control any trunk motion; they simply hold the bones together. The lumbar region is also supported by the iliolumbar ligament. In addition, the thoracolumbar fascia supports the structure of the thoracic and lumbar regions, particularly in full flexion of the trunk, and assists with initiating extension.

Muscles and Their Actions

The main spinal extensor muscle groups are the erector spinae (iliocostalis, longissimus, and spinalis), which are the largest muscles contributing to extension, and the deep posterior muscles (intertransversarii, interspinales, rotatores, and multifidus), which contribute also to supporting and maintaining rigidity of the vertebral column as well as producing finer movements within the trunk[36]. These muscles are located longitudinally along the spinal column in pairs on the right and left sides. If both muscles of the pair are activated simultaneously, then extension occurs. However, if only one side is activated, axial rotation and/or lateral flexion will occur. As shown in a study by Al-Eisa, rotations of the spine in other planes will simultaneously occur while trying to perform a principal rotation if not cancelled out by neutralizer muscles[46].

Flexion of the lumbar spine is created mainly by the abdominal muscles (rectus abdominis, internal obliques, external obliques, and transverse abdominis), with some help from the psoas major and minor[36]. The obliques and the transverse abdominis muscles also provide support to the trunk. Finally, in the lumbar region specifically, the iliopsoas and the quadratus lumborum contribute to flexion of the trunk.

Trunk lateral flexion is created by contracting the muscles on both sides of the vertebral column but primarily by muscles on the side that the trunk is laterally flexing[36]. Particularly, activity mostly occurs in the lumbar erector spinae and the intertransversarii and interspinales muscles on the ipsilateral side. The quadratus lumborum on the side of the lateral bend and the abdominals also contribute to this movement.

Finally, for axial trunk rotation, the multifidus muscles in the lumbar region on the side of the direction of rotation and the longissimus and iliocostalis muscles on the contralateral side produce trunk axial rotation[36]. Also, the internal oblique on the side of rotation is active while the external oblique on the opposite side is active.

Tissue Mechanics of Muscle and Connective Tissue

The flexibility of the trunk in any direction is limited by articular anatomical restrictions, constraining mechanical properties of musculo-skeletal and other soft tissues within the trunk, activation of reflexes through somatosensory receptors within the spinal tissues, and the tolerance of perceived discomfort[37]. Muscles are viscoelastic and thixotropic, meaning that they are less viscous when a stress is applied. Because of thixotropy, they always have some stiffness and can passively resist strain to some degree. This is commonly referred to as muscle tone[37]. They also exhibit stress relaxation (stress generated by tissue decreases with time when the tissue is held at constant deformation), hysteresis (some amount of mechanical energy that was added to the system when loaded is converted to non-mechanical energy when the load is released), and creep (at a constant load, deformation increases over time)[47]. At higher rates of stretch, the viscoelastic property of rate sensitivity causes increased musculo-tendinous stiffness, perhaps due, in part, to titin, a molecular spring attached in series between the Z-disk and M-line of the muscle sarcomere.

The tendons and ligaments within the trunk are made up of collagen fibers and are also viscoelastic. In addition, these tissues are also made up of differing levels of elastin, therefore the viscoelastic properties of individual tendons and trunk ligaments are very individual tissue-dependent[30,48]. One effect of elastin levels is that the length of deformation in the toe region varies. For example, as previously mentioned, due to its high levels of elastin, the ligamentum flavum has high elasticity and a long toe region compared to the tendons in the erector spinae muscles that have low levels of elastin[30,48]. In the toe region of a stress-strain curve for ligaments, these fibers have a natural crimp that straighten when tension is applied at low strains[49]. The toe region for tendons and other ligaments, besides the ligamentum flavum, allows relatively small strains (limits between 1-2% for the longitudinal ligaments of the spine[50])[49]. As increased stress or strain past the toe region occurs, loading response is in the linear region. The slope of this region indicates the stiffness of the tendon or ligament. These tissues tend to be relatively stiff and the stiffness within this region increases as strain rate increases[49,51]. After the linear region, failure begins to occur as individual collagen fibers begin to break. When this occurs, the load must be distributed among the remaining intact fibers, increasing their stresses. Eventually, if the load, and thus, the stresses continue to increase, the tendon or ligament eventually fails.

Several somatosensory receptors are sensitive to mechanical movement in the muscles, connective tissues, and the joints. First, when muscle fibers are stretched, the primary muscle spindles undergo deformation, triggering the stretch reflex that causes greater muscle activation to increase contractile force [30]. These muscle spindles lie parallel to the muscle fibers and are wrapped around each fiber. The secondary muscle spindles are also activated when the muscle is overstretched. In addition, during a rapid muscle contraction, typically an eccentric action, whereby the tendon is under rapid tensile loading, Golgi tendon organs, connected directly to extrafusal fibers of the muscle, ensure that active muscle force does not exceed the limits of what the tendons can handle[30]. They are particularly sensitive to tension more than contraction causing it to be more responsive to small changes in eccentric force. When they are stretched, either passively or actively, the strands of collagen excite these sensory receptors and cause the muscle contraction force to be reduced. Smaller muscle forces are required to activate the receptors during an active stretch than during a passive one. Finally, Ruffini endings and Pacinian corpuscles are located within the synovial joint capsules[36]. Ruffini endings are tactile receptors, sensitive to joint position and velocity. The Pacinian corpuscles respond to pressure created by muscles.

Mechanisms of Rib/Abdominal Injury

Two mechanisms of rib injury can occur. For the first ten ribs, connected by a costal cartilage articulation, traumatic stress is usually due to compression of the thorax. The ribs allow substantial in-bending before there is any fracture which causes compaction of the visceral organs[14]. Transverse fracture usually occurs due to blunt trauma just anterior to the costal angle of the rib, the weakest point of the rib[13,14]. This fracture is also called lateral fracture of the ribs[14]. However, secondly, in the event of lateral compaction, more fractures tend to occur near the vertebral or sternal ends of the ribs[14]. Following a direct anterolateral blow to the chest, the 4th through the 9th ribs are most often fractured[13,14] with the chondral rib fractures occurring mostly from the 6th to 8th ribs[10].

With rib fracture there often is concurrent risk of solid organ injury[16]. Particularly, fractures of the lower two ribs due to direct blow have a large risk of affecting the kidneys, liver, and spleen[38]. This is likely due, in part to the free anterior ends of 11th and 12th ribs[38]. For kidney injuries of NFL players, reported by Brophy et al., a vast majority of them were due to contact, often from a tackle[18]. Pulmonary contusions (bruises of the lung associated with hemorrhage and edema) are caused by either sudden decelerations of the upper body causing the lung to hit the chest wall, heavy blows to the chest causing compression of the lung, or a displaced rib fracture[38].

Trunk Range of Motion

Because of the presence of the ribs and the orientation of the vertebrae in the thoracic region of the vertebral column, there is limited movement. Overall, the range of motion of the thoracic region for flexion/extension is approximately 3° to 12°[36,45]. However, the upper thoracic region has very limited range of motion (2° to 4°) while the thoracic range of motion increases caudally to the lower thoracic region up to 20° at the thoracolumbar junction. For lateral flexion, the range of motion is limited, ranging from 2° to 9°, with the upper thoracic ROM lowest (about 2° to 4°) and the lower thoracic ROM being as high as 9°. However, for axial rotation, ROM decreases caudally, and the thoracic segment ROMs ranging from 2° to 9° [36,45].

The lumbar region has the greatest total flexion/extension range of motion among the spinal segments, ranging between 52° and 59° for flexion and 15° to 37° for extension[36,45]. At each vertebra there can be between 8° and 20° of motion. Lateral flexion and rotation are more limited, however, with a total range of motion of 14° to 26° and 9° to 18°, respectively. At the individual vertebral levels there is 3° to 6° of lateral flexion and 1° to 2° of axial rotation.

Trunk Flexibility Protocols

Several methods have been used to assess trunk flexibility of healthy populations[52–54], clinical populations (low back pain[46]), athletic populations[55–58], elderly populations[59], and children[60]. Several studies have looked at all three directions of trunk flexibility[52,53,55]. Hsu et al. looked at ranges of motion while standing[52] while Krutsch et al. looked at all ranges of motion while sitting in conjunction with strength[55]. Alaranta et al. looked at a combination of start positions[53]. For flexion, the participants touched their toes. However, for extension, participants started in a prone position and arched their back as much as possible. For rotation, they were seated while holding a bar behind their shoulders[53]. Finally for lateral flexion, they stood against a wall and bent as far as they could to either side. Aragon et al. used a similar flexibility protocol for rotation but also included half kneeling and standing while holding a bar[56]. This flexibility measurement was taken in softball players and related to their throwing arm dominance. However, results showed that the type of flexibility protocol did not have an effect on flexibility values.

Both Yoshida et al. and Al-Eisa et al. looked at two directions of movement[46,54]. Yoshida had participants touch their toes (flexion) and bend all the way backward (extension) while standing to measure range of motion in the sagittal plane[54]. For lateral flexion in the frontal plane, participants stood freely and bent to either side with their arms along their sides. Al-Eisa measured range of motion in the frontal plane similarly on participants with low back pain while also including the same measurement while seated in a backless chair[46]. However, axial rotation range of motion was also measured, both seated and standing, by having participants rotate as far as they could to either side. This study found that range of motion values were higher in axial rotation when the participant was sitting and higher in lateral flexion when the participant was standing[46]. This is likely due to the pelvis being fixed during rotation while the participant is seated and the arms not being obstructed during lateral flexion when the participant is standing.

Finally, Kim, Mohammed, and Castro-Pinero each looked at one axis of rotation for range of motion of the trunk[57,60,61]. Mohammed and Castro-Pinero both used the sit and reach test to measure flexibility through trunk flexion[57,60], while Kim used the lateral leg reach test to measure axial trunk rotation flexibility[61].

All previously discussed studies were conducted actively, without assistance from researchers, and at a self-selected pace. Self-selected paces have been shown to produce more controlled movements through a full range of motion[46]. However, the range of motion values for self-selected trunk flexibility protocols vs maximal speed protocols are consistent[62]. Laudner et al., however, looked into trunk flexibility in the sagittal (flexion-extension) and transverse (axial rotation) planes while standing using an active-assisted protocol[58]. Initially, the movement was started by the participant but was then continued by a researcher at the ends of the ranges of motion. Researchers are able to take into account movements due to momentum through the use of passive protocols[56].

Overhand Football Passing

The overall performance objective of an overhead football pass is to project the football down the field to the athlete's teammate as quickly and as accurately as possible. With overhand throwing, an athlete is able to use forces and torques transferred from the legs all the way to the hand at release[28]. Overhand throwing in baseball and football passing has slightly different kinetic and kinematic characteristics due to the different performance goals and weights of the balls[29]. Still, the similarities between football passing and pitching overlap so much that much of the research focused on baseball pitching can also be applied to football passing[63].

Phases and Purposes

Traditionally overhand throwing has been defined by six phases: wind-up, stride, arm cocking, arm acceleration, arm deceleration, and follow through[28,63]. However, a study by Kelly et al. used electromyographic analysis to reduce football passing specifically into four major phases: early cocking, late cocking, acceleration, and follow through[64].

In the traditional phases of overhand throwing, the wind up phase is used to put the thrower in a good starting position[28]. This phase begins when the athlete begins movement and ends when the lead leg lifts to its maximum height, which is usually not high in football passing. During this phase, both hands are on the ball. During the stride phase, the thrower generates linear velocity towards the intended target and the hands begin to separate[28,63]. The abduction of the arms during this phase allows the muscles to be stretched storing elastic energy and activating the stretch reflex to allow muscle contraction to be enhanced[28]. In addition, torque begins to generate up the kinetic chain due to the internal rotation of the stance hip. The sequence of oblique activation in this phase along with other trunk muscle activations in later phases allows the trunk to generate high forces and energy[65,66]. The stride phase concludes when the lead leg touches the ground[28,63].

The third phase, arm cocking, begins at lead foot contact and ends when the throwing shoulder is maximally externally rotated (greater in football passing than a baseball throw)[28]. During this phase, the arm cocks backward while the trunk and legs rotate forwards. At the very beginning of this phase the pelvis begins to rotate forward followed closely by rotation of the upper torso. During these rotations, elastic energy is stored through the stretch of the abdominal and oblique muscles because of the lag between the pelvis and upper torso and the hyperextension of the trunk[28]. A vast majority of the power generation during a throw comes from the hips, torso, and shoulders[27] and lead to the greatest percentage of force generation during ball acceleration[67]. Timing of the pelvis and trunk therefore is extremely important during this phase since improper rotation sequence can lead to increased stresses at the shoulder[68]. By the end of the arm cocking phase, the legs, hips and trunk no longer continue to accelerate[63]. The accelerations of the pelvis and upper torso during a football pass are less than that of a baseball throw[28]. Just before the end of the arm cocking phase, the elbow begins to extend to allow the shoulder to internally rotate in the next phase with as little resistance as possible.

During the arm acceleration phase, starting from maximal shoulder external rotation to ball release, the force generated through the kinetic chain is applied to the ball to accelerate it before release[28]. The trunk begins to flex from its hyperextended position to a neutral position. The abducted shoulder internally rotates and the elbow continues to extend at high velocities. The elbow reaches maximal extension velocity in the middle of arm acceleration while the shoulder reaches maximal internal rotation velocity at ball release. Arm deceleration then occurs from ball release to maximum shoulder internal rotation[28,63]. This phase is usually very short and purposes to slow the arm down. During this time, the trunk and hips continue to flex while the lead leg and throwing elbow continues to extend. Overall, there is less trunk tilt in football passing than in baseball pitching[28,29]. In addition, the arm begins to horizontally adduct across the torso[63].

Finally, the follow through phase begins at maximum shoulder internal rotation and ends at maximal horizontal adduction of the arm[28]. Energy is transferred to the musculature of the trunk and legs during this phase to avoid overly stressing the throwing arm. The follow through is shorter for a quarterback during football passing compared to a baseball throw due to the quick adjustment these players must make to receive a tackle.

As mentioned, Kelly et al. used electromyography to classify four phases of overhand football passing[64]. Early cocking began at stance foot plant and ended when the shoulder was maximally abducted and internally rotated. Late cocking was initiated at the end of early cocking and ended with maximal shoulder external rotation. The acceleration phase then started with maximal shoulder external rotation and ended at ball release, and the follow through was from ball release to maximal horizontal adduction. Kelly reported that the shoulder initially internally rotated as the shoulder abducted during the early cocking phase[64] instead of the shoulder externally rotating and abducting at the same time during the arm cocking phase in Fleisig and Weber's phase definitions[28,63]. The shoulder then externally rotated by itself in the late cocking phase[64]. The period within the throw that Kelly classified as the 'acceleration' phase and Fleisig and Weber's 'arm acceleration' phase were started and ended at the same critical events[28,63,64]. The arm deceleration and the follow through phase defined by Fleisig and Weber were combined into one phase (follow through) in Kelly's study.

Throwing Performance Measurement

Stodden et al. has shown that ball velocity is largely dependent on degree of trunk tilt and linear and rotational trunk velocities[26]. Roach and Lieberman have shown that when the trunk specifically is braced to limit range of motion, throwing performance parameters such as ball velocity and torso angular velocity decreases[27]. In addition, numerous studies have studied throwing accuracy and throwing velocity in baseball[28]. However, to my knowledge, no studies have been conducted to measure throwing performance in football. Several studies have looked at throwing speed[69–73] and two recent studies have looked at throwing accuracy in water polo[70] and team-handball[73] but throw performance measurements are limited. Within the studies discussed, only a few mentioned methods for measuring throwing speed or accuracy. Radar guns seem to be the most commonly used method of measuring throwing speed[71,74] while grid targets, with either scored zones or measurements from the center of the target, seem to be the most commonly discussed method of measuring throwing accuracy[74].

CHAPTER 3:Methodology

For this project, there are two sub-studies described. The same group of individuals participated in both sub-studies and all data was collected in a single 2.5 hour session.

Research design

Cross-sectional, quasi-experimental repeated measures design.

Independent variables:

Throwing Sub-study: Rib protection group (control and rib protector: soft-rib, hard-rib)

Flexibility Sub-study: Rib protection group (control and rib protector: soft-rib, hard-rib); type of flexibility protocol (SS, AA, MS).

There will be two separate sub-studies described.

Participants

An a priori power analysis for non-inferiority testing (power = 0.8, α = .05; Sealed Envelope™, 2012) using data from a throwing pilot study and a previous flexibility study,[56] determined that 5 to 35 participants would be needed to detect non-inferiority less than 3° in displacements for flexibility and throwing. However, after collecting data for 8 participants and setting the non-inferiority margin (NIM) to one standard deviation of the control condition, a power analysis was re-run and determined that between 2 and 25 participants were necessary to determine non-inferiority. Due to the small population of adult competitive quarterbacks available on the campus of University of Georgia and in the surrounding community, 12 participants were successfully recruited and tested for throwing and 11 for flexibility. According to the power analysis, this would result in .80 power for 7 of the 11 variables for soft-rib and 10 of the 11 variables for hard-rib in throwing.

All participants were:

a) Male
b) 18 to 35 years old
c) A current or former quarterback on an intermediate or advanced level American football team (e.g., high school varsity, college, professional, semi-professional, etc.)
d) Currently engaged in moderate and/or vigorous activities at least 2.5 and/or 1 hour(s) per week, respectively[75].

Exclusionary criteria

1. A history of spinal surgeries, tumor, fractures, scoliosis, or other diagnosed spinal disorders.
2. A history of upper extremity surgeries or injuries in the throwing arm without undergoing formal rehab and returning to same level of play.
3. Acute injury to the muscles or joints of the throwing arm, legs, and/or the spine or trunk in the previous 6 months that resulted in health care provider visit or limitation of physical activity secondary to injury.
4. Reported experiencing any unusual symptoms, preventing participation in physical activity.

Rationale behind participant selection

All participants were male as the vast majority of individuals who have played competitive American football as a quarterback on, at the required (or higher) skill level are male. The particular playing position chosen was one that is subject to large impacts from defensive players and often must complete overhand football passing in game settings. Quarterbacks are not required to wear rib protection but may do so voluntarily.

Instrumentation

For both sub-studies, a 7-camera Vicon MX™ motion capture system (Vicon-MX40, Vicon Motion Systems Ltd., UK) sampling at 240 frames/sec, was positioned around the testing area to capture trunk motion. Twenty-three 14 mm-diameter markers were placed on the legs, throwing arm, trunk (clavicle, sternum, right back, left and right shoulders), and pelvis using the Full Body Plug-In-Gait Model (Vicon Motion Systems Ltd., UK) marker set based on a Modified Helen Hayes lower body model[76]. In addition, two additional 14 mm-diameter markers were placed on the highest points of each iliac crest. A forearm (four 14 mm-diameter markers), upper arm cluster (four 14mm-diameter markers), and a two 14 mm-diameter marker wristband was put on the throwing arm. Finally, three marker cluster sets (shown in Figure 3.1a) were placed on the C7, T8, and L3 spinous processes. Only the T8 and L3 marker clusters were used to calculate lower thoracic relative angles for these sub-studies. Two 14 mm-diameter markers were placed on the football to detect the instant of ball release. For all conditions, all upper body markers (above the pelvis), were placed directly on the skin except for the sternum, right back, and, in the hard-rib and control conditions, the clavicle. In addition, all markers below the cutoff of the compression shorts and above the shoe were placed directly on the skin. Foot markers were placed on the shoe and pelvis markers were placed on the compression shorts. For each spinal marker cluster, the base was placed directly on the skin and fed through a very small hole (4 mm-diameter) in the compression shirt portion of the rib protector garment to meet the rod of the marker cluster where the rod was screwed into place. The locations for all markers that were placed on the rib protector garments were marked with washable marker on the participant prior to marker placement to ensure that the marker locations were the same for each rib protector condition. The full marker set is shown in Figure 3.1b.

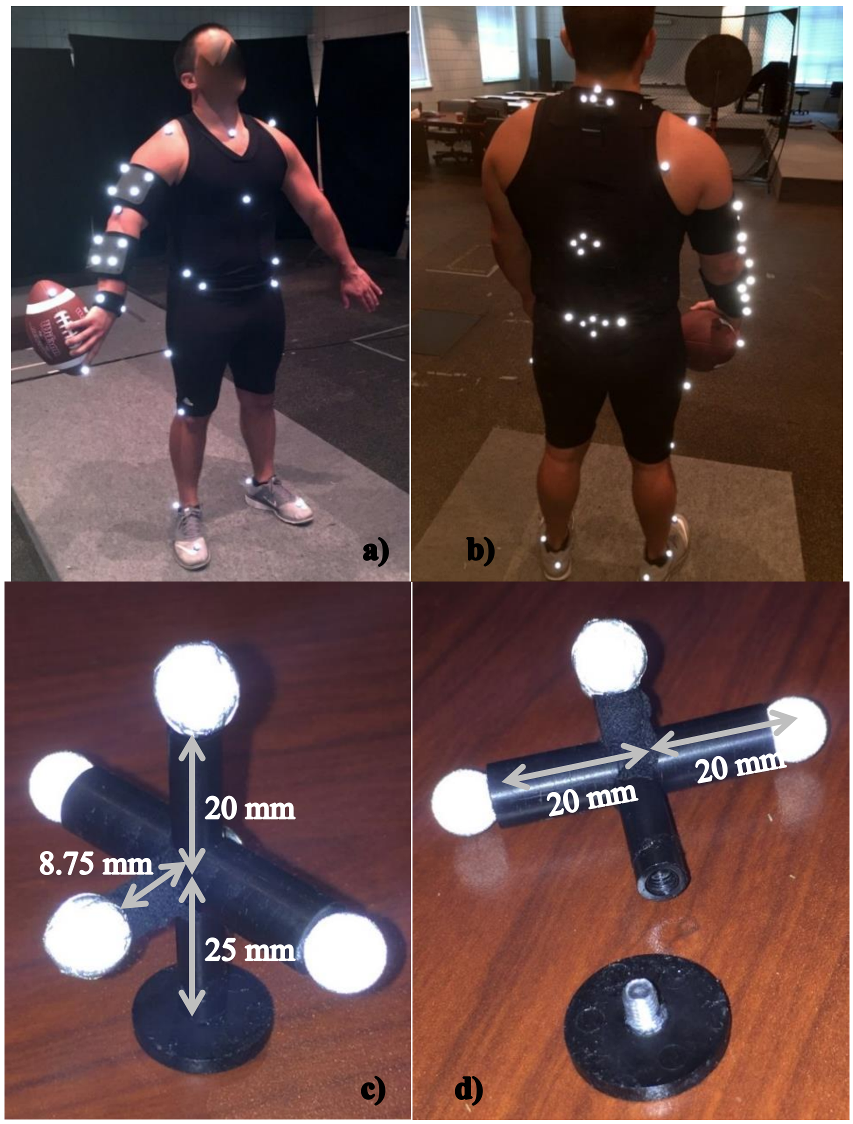

Figure 3.1 — Marker set. (a) Front view and (b) back view of the full marker set used for motion capture. Additional markers not used in this study were placed on the participant. (c) An assembled example spinal marker cluster set. (d) An unscrewed spinal marker cluster set. Marker sets placed on the C7, L3, and T8 vertebrae, were made of four 9.5 mm-diameter markers attached to a base consisting of a 6.6 mm-diameter vertical plastic rod crossed with a 9.7 mm-diameter horizontal plastic rod; a 3 mm-diameter screw,

protruding from the 3 marker plane, covered with black tape; and a19.1 mm-diameter solid plastic base with a 4 mm-diameter screw projecting from it into the horizontal rod. The base was placed on the skin and fed through a small hole in the garment.

In addition to motion capture, for sub-study 1, vertical ground reaction force was obtained using one of two (depending on step width of the participant) tandem force plates (Bertec 4060-NC) sampling at 1200 Hz. Finally, a Bushnell® radar gun was used to measure the football speed after release.

Experimental Tasks and Setup

Sub-study 1: Overhand Football Throwing

The participant started in a natural standing position facing the target with their feet shoulder width apart centered (indicated by a hash mark) along a line in front of the two force plates, shown in Figure 3.2. With both hands on the football, they then completed a single-step drop-back motion onto one of the force plates behind them. They then threw the ball as hard and as fast as they could to a .914 m-diameter chalked bullseye target, shown in Figure 3.3, with a tape measure attached to the center.

A .914 m-diameter target along with a square net placed directly behind it was 9.144 meters away from the participant's starting position. A researcher stood behind the net with a radar gun to measure how fast the ball was moving. The experimental setup of the study is shown in Figure 3.4.

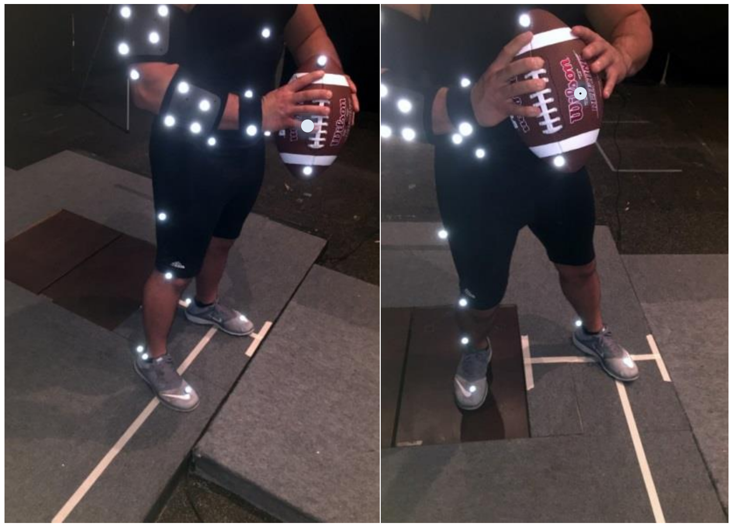

Figure 3.2 — Single-step drop-back. **(a)**Starting position for the throwing task. **(b)** Position after single-step drop-back and before throw.

Figure 3.3 — .914 m-diameter chalked throwing target with a tape measure attached to the center.

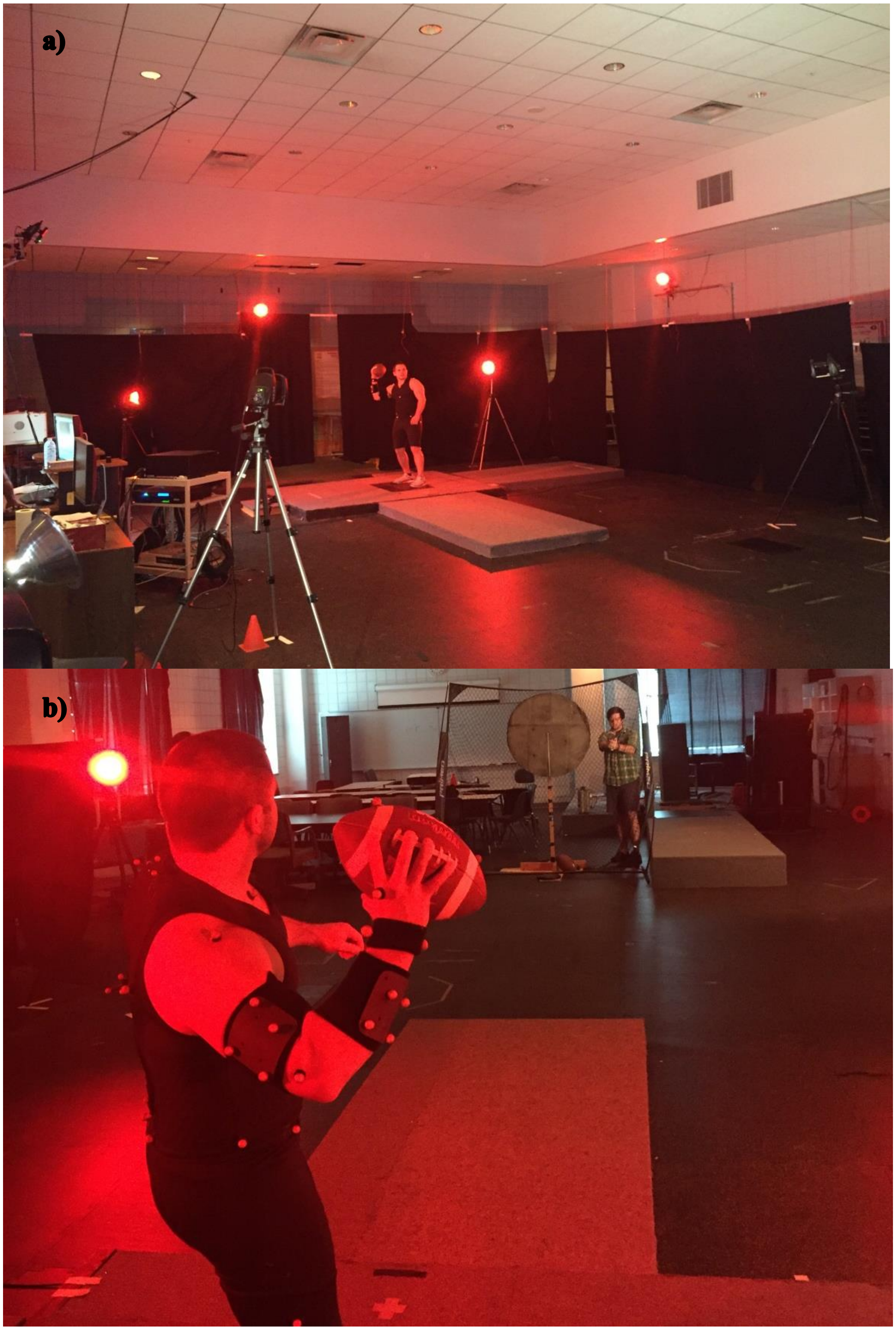

Figure 3.4 — The experimental setup for this study: **(a)** Front of participant view **(b)** Behind participant view. A 7-camera Vicon motion capture system surrounded the capture area. The participant threw the ball to a target 9.144 m away while a researcher measured ball speed with a radar gun.

Sub-study 2: Trunk Flexibility

The participants started in a neutral standing (for lateral flexion) or seated (for axial rotation) position facing forward to begin every flexibility protocol. The flexibility protocols and each rotation direction were completed in a quasi-counterbalanced order. The experimental setup was similar to sub-study 1. Two weighted poles were used for the active-assisted flexibility protocol.

Protocol

For each condition, all test tasks of sub-study 2 were conducted before the test tasks of sub-study 1. These tasks are, therefore, described in the order of testing.

Eligibility screening: Before coming to the lab, a potential participant was consented for engaging in the first screening for eligibility and asked questions over the phone to ensure that, tentatively, all previously stated criteria were met as approved by the Institutional Review Board (IRB). If eligible, the date for data collection was set up.

Preparation: Upon arrival, the participant filled out the Informed Consent, along with a Current Health Status Questionnaire and a Physical Activity History Questionnaire to further ensure that he was eligible to participate as approved by the IRB. If the individual was still eligible to participate, then the data collection was conducted. Black compression shorts and the participant's own low top running or cross-training shoes were worn by the athlete. Anthropometrics (height, mass, leg length, knee width, ankle width, shoulder offset, elbow width, and wrist width) were taken using Dempster's model[77]. Arm dominance was determined by asking the participant which arm was their throwing arm. The order that the rib protector conditions were tested was counterbalanced.

For each rib protector condition of each sub-study, the bases of the marker clusters were placed on the C7, T8, and L3 vertebrae and the rib protector was then fitted to the participant. The rest of the markers were then placed on the participant before completing the test tasks of each sub-study. The participants then rated their perceptions of the rib protector condition, on the basis of mobility, comfort, protection, and performance on a 101 mm Visual Analog Scale (VAS). After the test tasks were completed, the participant then rated their perceptions on the VAS again on a new sheet where their previous answers were blinded and then repeated the process for the next rib protector condition. There were at least ten minutes of rest between the previous condition's throwing task and the start of the next condition's flexibility task. When all tasks had been completed, the Rib Protection Ranking Questionnaire was filled out.

Sub-study 2:Trunk Flexibility

Pre-Test Tasks: Participants were instructed to warm up on the treadmill at a self-selected pace for 2-5 minutes and lightly stretch their back in each direction (axial rotation, lateral flexion, and forward flexion/extension) three times each direction for 5 seconds each. Participants were then told that they would complete a series of flexibility measurement tasks. Each task was demonstrated to them by a researcher right before the performance of the trial and they had a chance to practice it until they got the correct motion.

Test Protocol: All participants started off with a static calibration trial in order to define later the coordinate systems for the segments. They stood in a natural position with their thumbs facing forward (palms facing the sides of their legs) for 3 seconds. The order that they completed each flexibility protocol was quasi- counterbalanced. Participants had one minute of rest between the flexibility protocols and ten seconds of rest between each trial and direction of movement within the flexibility protocols. Three trials were performed for each flexibility task.

For the self-selected speed (SS) flexibility protocol[46]*:*

The participants completed the movements at their own pace but were advised to take their time to ensure that they rotated or reached as far as they could and that they were not moving too fast. In addition, for this and all consequent flexibility types, they were told to ensure that they reduced flexion and extension and lateral flexion as much as possible for the lateral flexion tasks and axial rotation tasks, respectively. For axial rotation, they started off seated on and legs strapped to a platform with their knees slightly flexed facing forward. They then actively turned as far as they could to the left, then as far as they could to the right, then as far as they could to the left again, and then went back to a neutral position. For lateral flexion, they started off standing with their feet about shoulder width apart. They then reached down to the left as far as they could and in a continuous movement reaching down to the right back to the left, and then returned to neutral. A researcher monitored the movements to ensure adherence to the protocol, and corrected them if undesired movement occurred.

For the active-assisted(AA) flexibility protocol[58]*:*

The participants completed the same movements described for the SS type with some slight additions. At both ends of their active range of motion for axial rotation, they then placed their hands flat on the ground on the side of rotation and pushed parallel to the surface to cause the trunk to slightly increase rotation without causing discomfort, as shown in Figure 3.5a-b. For lateral flexion, they pulled on one of two 13kg weighted poles on either side to continue further lateral flexion on either ends of the range of motion without discomfort as shown in Figure 3.5c-d.

For the maximal speed (MS) flexibility protocol:

The participants completed the same movements as they did for the SS protocol but at maximal speed.

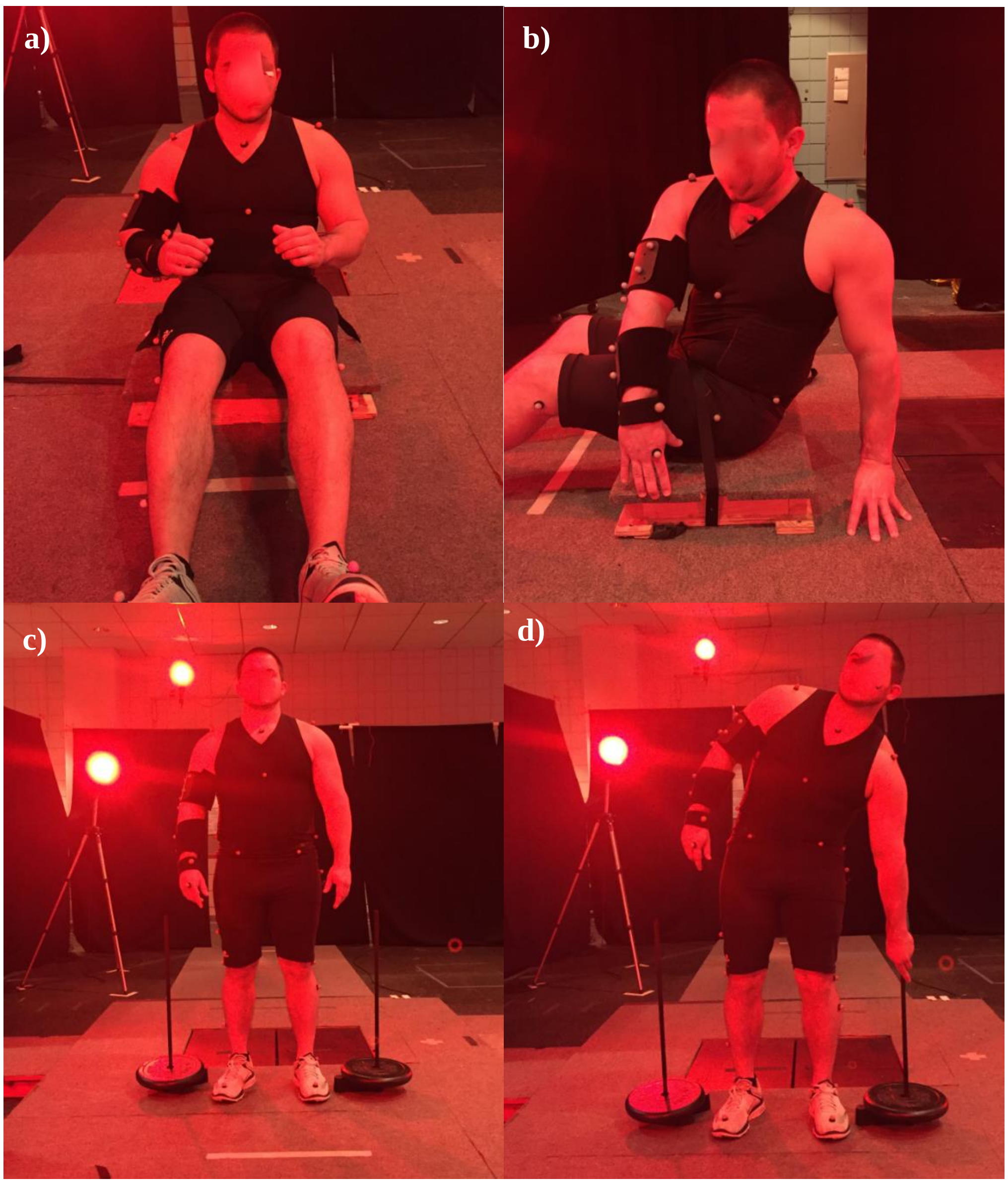

Figure 3.5 — Active-Assisted Flexibility Protocol. **(a)** Starting position of the axial rotation active-assisted (AA) flexibility type. **(b)** Passive portion of the axial rotation AA type. **(c)** Starting position of the lateral flexion AA flexibility type. **(d)** Passive portion of the lateral flexion AA type.

Sub-study 1: Overhand Football Throwing

Pre-test Tasks: After completion of the flexibility protocol, participants completed 10 arm rotations in each direction within the sagittal plane, followed by 10 horizontal abduction/adduction arm swings. They were then instructed to repeat this stretching sequence again.

Participants were informed to throw at maximal effort with highest accuracy at center of target using the single-step drop-back technique, and they must stay within the boxed area while completing each throw. They were told to begin with both feet facing forward along a preset line with both hands on the ball. On go, they were told to pivot on the non-dominant foot and land their dominant foot fully on one of the force plates as quickly as they could. Upon touching the force plate they were instructed to throw the ball as hard and as fast as they could to the target. A researcher demonstrated the technique to the participant while explaining to avoid any confusion.

Test Protocol: The participants first completed another static calibration. They then completed a self-selected arm and throwing warm-up followed by five practice throws (including the single-step drop-back) at 50% effort to ensure they were properly completing the task. The starting position of the feet was marked with tape during the practice trials to ensure that they began at the same spot for every throw. Upon completion, they then began the actual test trials. The target was fully covered with chalk at the beginning of each trial to ensure that the accuracy of the throw could be properly measured on the target. On cue, the participant then performed a single-step drop-back and threw the ball at maximal effort to the target. The ball mark on the target was then measured from the center of the bullseye to the center of the mark and recorded. Ten acceptable trials were collected. An acceptable trial was visually determined by the researchers ensuring that:

1) Both hands started on the ball
2) The participant stepped directly backward with the back leg landing completely on one of the force plates
3) The participant stepped backward with the same leg as the throwing arm
4) The ball hit the target.
5) The ball marked the target where it hit.
6) The radar gun took an accurate speed measurement.

There were 20 seconds between each trial to minimize the effects of fatigue. The target was re-chalked and the participant then began the next trial.

Data Reduction

For the throwing task, the top five trials determined by a composite score (2*[45-throw error] + ball speed) were analyzed. The phase analyzed was a newly defined 'pelvic acceleration phase' (initiated at touchdown of the back foot on the force plate and ending at ball release). This phase was chosen because it spans all trunk motion that contributes to ball speed and accuracy.

Angular Kinematics

At least six data points were kept before and after the phase of interest for filtering purposes. The raw two-dimensional marker locations from each camera were converted into three dimensional coordinates using the Nexus software proprietary algorithm (Vicon- MX40, Vicon Motion Systems Ltd., UK). A 4^{th} order Butterworth low-pass filter was used on all kinematic data. This filtering method was determined to be the best method for filtering quick axial trunk rotations in previous pilot studies. In addition, this method tends to reduce high frequency noise without removing too much of the signal due to the sharp 'roll off'[78]. The cutoff frequency was determined as 4 Hz for throwing and 2 Hz for flexibility using a power spectrum analysis. A modified Helen Hayes model with additional spinal markers and rigid marker clusters was used to define the origins and orientations of segmental coordinate systems[76].

The T8 and the L3 vertebrae were reconstructed with the origin on the spinous processes of each vertebra and right lateral flexion (X), flexion (Y), and left axial rotation (Z) defined as positive, as shown in Figure 3.6[79]. The relative angle of the T8 vertebra in reference to the L3 vertebra was calculated with the filtered trajectories using the Cardan method in an X-Y-Z rotation sequence. Corresponding relative velocities and accelerations were then calculated. The time to peak axial acceleration began at touchdown on the force plate and ended at maximum (positive) axial acceleration.

For the overhand throwing task, axial rotation towards the anterior direction (towards the target), for presentation purposes, was positive. Therefore, right-handed throwers showed positive values for rotation to the left and left-handed throwers showed positive values for rotation to the right.

Linear Kinetics

For the VGRF data, a 4th-order Butterworth low-pass filter, with a cutoff frequency of 300 Hz determined based on a power spectrum analysis was used to remove noise from the raw GRF data. GRF was solely used to determine the time at initial contact of the stance foot. Initial contact was defined as the instant in time when the vertical GRF magnitude first reached a value of 10 N or greater [80].

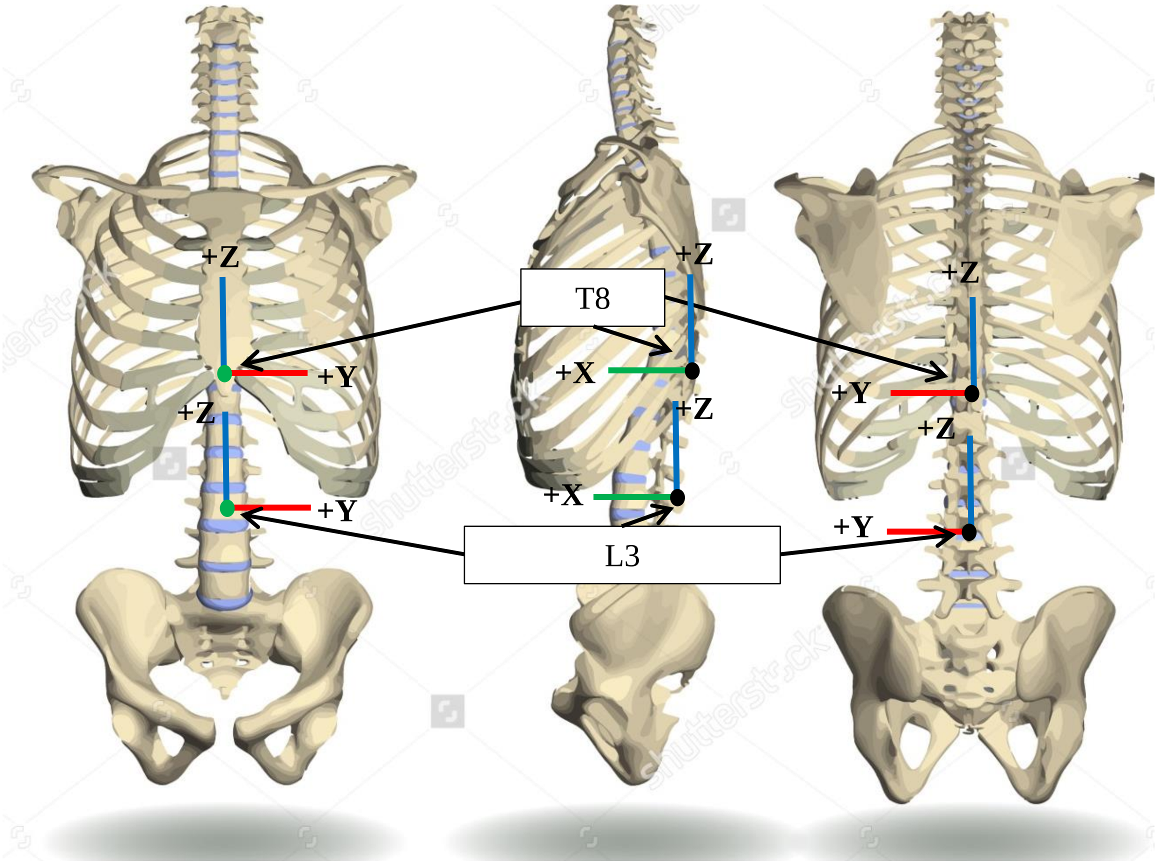

Figure 3.6 — Axis directions and origins (located on the spinous processes for vertebrae and the center between ASIS for pelvis) for T8 and L3. Green represents +X, red represents +Y, and blue represents +Z.

Performance measures

For the overhand football throwing task, the time to complete the throw for each trial began at the start of the trial (when the researcher said go) and ended at ball release. The ball speed was determined by a radar gun during each trial. Finally, the distance from center of target was be determined by the distance (in cm) from the center of the target to the center of the spot of missing chalk on the target.

Perception measures

VAS scales were measured from the start of the scale to the participant’s mark in mm and divided by total length (101 mm) of the scale to determine the score for each question. These values were used to interpret the results of the dependent variables.

Analysis

Sub-study 1: Overhand Football Throwing

For the top five throws of each rib condition, peak backward and forward relative rotation angles and peak relative displacement between these two angles in the axial plane between the T8 and L3 spinous processes were calculated in order to determine if a rib protector caused a change in trunk range of motion. Peak forward relative angular velocity and acceleration in the axial plane between the T8 and L3 spinous processes were calculated to determine if variables that would affect time to complete the throw and the amount of the force generated on the ball were affected by rib protectors. Finally, the time at peak forward relative angular acceleration was calculated as the time from touchdown of the stance leg until the time the maximum angular acceleration value was reached in order to determine if timings of the rotations had been affected by the rib protectors.

The time to complete the throw, the ball speed, and the distance from center of target were used as variables to determine if performance of the throw was affected by the rib protectors. For each variable, the averages of the top five trials’ values were obtained for each rib protector condition.

Sub-study 2: Trunk Flexibility

For the flexibility protocol, relative lower thoracic range of motions (between the T8 and L3 spinous processes) about the axial and lateral flexion axes were calculated as the difference between the maximum and minimum relative angles.

Statistical Testing

For each variable, in both sub-studies, outliers were removed according to the Rule of Huge Error[81]. Non-inferiority tests using a 95% confidence interval were conducted between control and each rib protector using the difference score (control value - rib protector value) using SPSS (Version 24 for Microsoft: SPSS Inc., Chicago, IL) for each dependent variable[82]. Non-inferiority was tested as opposed to superiority because it is only the goal of the study to show whether rib protectors will negatively affect quarterbacks in order to increase compliance. The non-inferiority margin (NIM) was set at one standard deviation of the control condition of the displacement found in sub-study 1 (throwing) for both studies. For the magnitude variables (ROM, displacement, velocities, etc.) individual rib protector conditions were ranked from the highest to lowest magnitudes, based on their confidence intervals. A corresponding example from Vavken[82] is shown in Figure 3.7.

For sub-study 2 (trunk flexibility), a 3 Rib Protector x 3 Flexibility Type Factorial Repeated Measures (RM) Analysis of Variances (ANOVA) was first conducted to determine if the same flexibility type could be used to test all conditions. Mauchly's test for sphericity was used to adjust p as necessary. In the event that the interaction was significant, the best flexibility type (highest values) for the control was used to analyze all data. If the interaction was not significant then the main-effect for flexibility protocol was analyzed to determine the best flexibility type for each direction of movement.

For the trunk ROMs in each direction, non-inferiority tests were conducted. The tests for the most appropriate flexibility type (as determined by RM ANOVA) were analyzed. A major limitation of this statistical test is that it is unknown what a clinical meaningful difference is for performance measures, axial trunk ROM, and flexibility as it has not been reported in the literature. In addition, the NIM which is based off a clinically meaningful difference has the power to determine the overall outcome of the non-inferiority test. However, choosing a value that represents the minimum detectable change beyond error is an acceptable way of determining the NIM[83]. Therefore, the non-inferiority margin (NIM) was determined as average of 1 standard deviation of the control condition of the participants for each protocol[83]. This represented typical variation seen in throwing or flexibility measurement without the use of a rib protector. Power was calculated for each non-inferiority test using the methods described in *Sample Size Calculations in Clinical Research*[84].

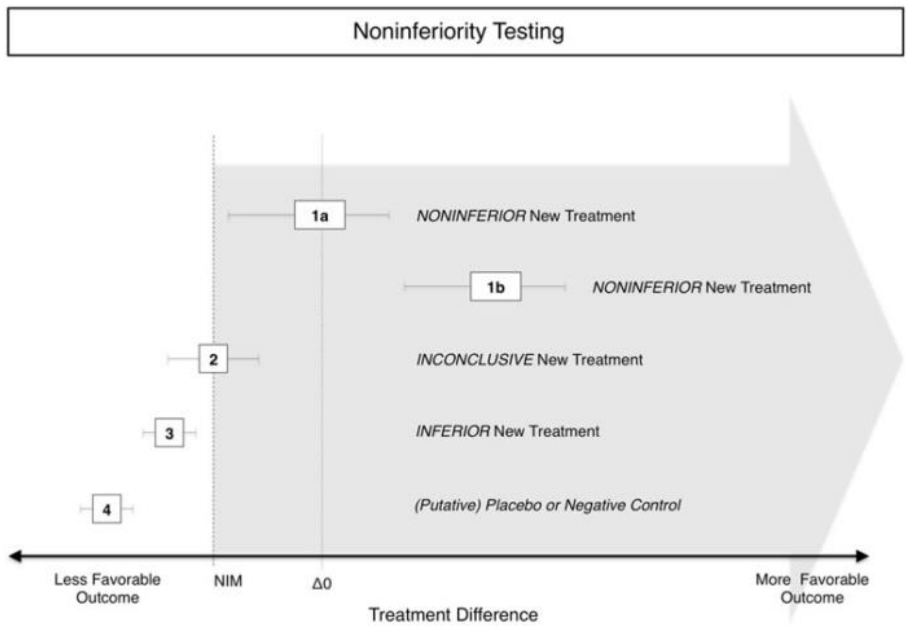

Figure 3.7 — The concept of non-inferiority testing as presented by Vavken[82] for medical or drug treatments trials in which new treatments are compared to the previously developed treatment. The treatment difference is the difference between the new treatments and the previously developed treatment. The Δ0 indicates no difference and the gray area spans from the non-inferiority margin (NIM) which is the lower range of what is considered to not be clinically different to anything performing better than the control. The CI for each number represents the 95%CI between the previous treatment and the new treatment. In my study, 1b = 95% CI for difference score between the control and a highest ranked rib protector on a given variable, e.g., maximum axial displacement. 1a = 95% CI for difference score between the control and a second highest ranked rib protector. 2 = 95% CI for difference score between the control and a third highest ranked rib protector that is inconclusive (not clear whether it is inferior to the control or not). 3 = 95% CI for difference score between the control and a fourth highest ranked rib protector that is inferior to the control but is inconclusive between 2 and 3. 4 = 95% CI for difference score between the control and a fifth highest ranked rib protector that is inferior to the control and inferior to 3.

CHAPTER 4: The effect of hard and soft rib protector garments on trunk kinematics, performance, and perceptions of quarterbacks during an overhand football throw[1]

[1] Walker, M. A., Samson, C. O., Simpson, K. J., Foutz, T., Brown-Crowell, C. N. To be submitted to *Journal of Applied Biomechanics*

Abstract

Rib protectors may help reduce serious rib injuries to American football quarterbacks. However, it is possible that offensive players may not wear them if perceived to hinder athletic performance. The study's purposes were to determine if hardness of two rib protector garments affected lower-thoracic axial-rotation kinematics and performance of a football throw, and whether perceptions were altered after throwing. Twelve male quarterbacks completed rib protector perception scales before and after ten maximal effort-accuracy throws during each counterbalanced rib protector condition: soft-rib, hard-rib, and control (compression shirt). Axial-rotation kinematics, ball speed, throw error and perception scores of each rib protector was compared to control using non-inferiority testing (group and within individual comparisons). Neither rib protector was inferior to control for axial kinematics or performance measures, but hard rib mobility was perceived to be inferior before and after wearing the protector. However, individuals responded differently to each rib protector for all outcome measures with some performing superiorly, some equivalently, a few inferiorly, and a majority having inconclusive results for most measures. Therefore, both rib protectors can be recommended, as neither appeared to hinder quarterbacks' performance or axial thoracic kinematics. However, it is important for individuals to choose the rib protector best for them.

Keywords: passing, mobility, throwing speed, throwing accuracy, non-inferiority testing, spinal kinematics

Word Count: 4,985

Introduction

During an American football game, offensive players are subjected to high impacts from defensive players, with momentums of up to 1,215 kg · m/s[1], leading to acute injury (ranging from mild to fatal) or long-term chronic effects on various locations of the body.

Lower-trunk impact events are concerning for two reasons. First, high-impact hits by opposing players often occur to the trunk, now the only contact area on the player's body where tackles and blocks are allowed. Since 2010, rule changes prohibit defensive players from tackling helmet first above the shoulders of any player in a 'defenseless' (not prepared for a hit) position[5]; or blocking below the waist. This may partly explain the increased number of injuries to the spine and axial skeleton in the U.S. National Football League, from an average of 197 per year (2000-2010 to 235 per year (2012 – 2013); total rib injuries during these two periods increased from 86 to 97[6,7].

Second, lower-trunk impacts are troubling because potentially serious injuries can occur. Injuries range in severity, from the common, relatively minor but painful rib and pulmonary contusions, to moderately serious rib fractures and costal cartilage ruptures, up to the most dangerous, that is, fatal solid organ injury [7–10] such as splenic or kidney rupture.

Rib and abdominal region protectors potentially could reduce prevalence and/or the severity of aforementioned injuries if more widely used[15,16]. Their effectiveness is difficult to ascertain at present, though, as evidence of injury-prevention efficacy, prevalence of use, and user compliance are not yet known. Consequently, the decision to have athletes wear preventative rib protection is not based on evidence, but on opinions based on personal experiences and perceptions of the equipment.

There are untested concerns that rib protectors may adversely affect performance achievement, the primary goal of an athlete. These concerns likely are based on perceptions that protectors restrict trunk motion and quickness, thereby reducing throwing accuracy and speed. Rib protector characteristics, such as compression, rigidity, and/or bulkiness of the protective padding in the compression shirt, likely create these perceptions.

In turn, athletes may not wear the protector if these characteristics are perceived negatively, as shown previously for use of other prophylactic injury devices (e.g., joint braces) [19–21]. This decision to not wear a protector may also be influenced by the belief that there is a relatively low likelihood that a severe lower-trunk injury will occur, in contrast to the risk of severe injuries to other body locations.[7,8]

Presently, there is no scientific evidence that performance or performance components (e.g., movement quickness, axial trunk mobility) are adversely affected by rib protectors. Therefore, quantitative evidence for making an informed decision about wearing a device that could improve a player's safety is needed. It also is important, if the athletes' perceptions of performance and performance characteristics are negative, to begin identifying the characteristics of the rib protection that contribute to these perceptions and to determine if they translate to decreased throw performance and trunk mobility.

Therefore, two variations of the 'garment' type of rib protection (Figure 4.1) were tested in this study. The protection area involves either one or more pieces of soft closedor open-cell foam padding (**soft-rib**) and/or a hard, protective, plastic plate with a thin layer of foam padding behind it (**hard-rib**) in the lower rib and/or spinal area that is embedded into a knit compression shirt (garment) worn underneath the football pads required during a game instead of the typical compression shirt or t-shirt.

Influence of rib protectors on throwing performance of quarterbacks was of interest because of quarterbacks' susceptibility to lower-trunk injury and their crucial role in the team's success. They risk being hit by defensive players every play, and when hit unexpectedly, the ribs (which have little muscle/adipose tissue for energy absorption) can be directly exposed to high impact forces[25]. For performance, quarterbacks must be able to complete passes quickly and accurately. Quarterbacks also may need more axial rotation and lateral flexion of the trunk than most other players[63]. Rib protectors could be very beneficial to quarterbacks, but only if their trunk motions and performance are unaffected.

Therefore, the first purpose of this study was to determine if a hard or soft rib/abdominal football protector garment compared to a control football compression shirt affects lower-trunk axial rotation (LT-AX-ROT) kinematics and performance (throwing speed and throw error) of quarterbacks during an overhand football throw. A second purpose was to determine whether protector hardness influences quarterbacks perceptions of performance and mobility and whether perceptions change after the player performs the throwing task.

We hypothesized that if wearing a compression shirt (control), adding either soft-rib or hard-rib protection would not lead to behaviorally-meaningful decreases for LT-AX-ROT kinematic or performance-related group outcomes. This was anticipated because the mechanical restriction of either rib protector was expected to constrain axial trunk kinematics due to the compressive properties of the garment in the region covered by the rib protection as well as the motion restriction due to stiffness of the protector, particularly the inflexible hard protector. However, the effects of mechanical restriction on trunk kinematics were expected to be low enough to be within the magnitude of inherent inter- or intra-participant variability of throwing. Moreover, if trunk kinematics are minimally influenced, then performance outcomes will not be affected. We also surmised that prior to performing the throwing task, athletes would perceive the rib protectors, particularly the hard-rib, to be restrictive and awkward, and thus score mobility (ability to move freely) and throw performance as lower than the control condition. However, after performing several repetitions of a functional throwing task, the perception scores for mobility and performance were anticipated to increase to non-inferior values, as the participant would not see noticeable decreases in their performance accuracy.

As athletes have shown different kinematic and perceptual responses to a particular athletic equipment feature[31–35] a differing outcomes among individuals were also expected. For example, due to lower trunk flexibility, some athletes use less trunk rotation than others. Therefore, mechanical restriction of the trunk area due to rib protection would have less of an effect on LT-AX-ROT kinematics, performance and perceptions of these athletes.

Methods

Twelve males (age: 23.8 ± 4.4 y, height: 179.89 ± 4.92 cm, mass: 89.64 ± 9.93 kg) with competitive quarterback experience (seven high school varsity, three collegiate, two professional players) took part in this study. Participants were required to be physically active and healthy; have no history of spinal surgeries, tumor, fractures, scoliosis, or other diagnosed spinal disorders; and to have undergone formal rehab and returned to the previous level of play after any upper extremity surgeries or injuries to the throwing arm. Institutional approval of protocol and informed consent was obtained before the study was conducted.

A cross-sectional, quasi-experimental, one-group design was conducted for group analyses. In addition, individual participant analyses among rib protector conditions were conducted. Three rib protector conditions were tested: soft-rib and hard-rib protector garments (Figure 4.1), and control. The soft-rib condition consisted of a sleeveless compression garment with individual honeycomb-shaped pieces of soft foam padding sewn into both rib areas and the lower spine region. The hard-rib condition also consisted of a sleeveless compression garment that contained hard moldable inserts on either side of the ribs. The side of the insert worn against the ribs consisted of stiff foam, while the outside of the insert consisted of hard plastic with honeycomb-shaped negative space. In addition, a flexible foam piece sewn into the garment covered the lower spine area. For the control condition, the compression garment of the hard-rib condition was worn without the inserts. Brand and model names were not visible to the performer.

Instrumentation: A 7-camera Vicon MX™ motion capture system (240 fps;Vicon®-MX40, Vicon Motion Systems Ltd., UK) was used to capture marker locations. Six 14 mm reflective markers were placed on the pelvis on the compression shorts or shirt (Figure 4.3a-b). Three-marker (9.5 mm) cluster sets (Figure 4.3c) were placed on the T8 and L3 spinous processes. Cluster set bases were placed directly on the skin and remained in place for all testing. Prior to testing a new rib protector condition, the screw of the base of the spinal marker cluster was fed through a 4 mm-diameter hole in the compression shirt portion of the rib protector garment to the rod of the marker cluster where it was screwed in place (Figure 4.3d). Two markers were placed on the football to detect the instant of ball release.

Vertical ground reaction force (VGRF) signals were obtained using a force plate (Bertec 4060-NC; 1200 Hz) to later determine the start of the phase of interest. A Bushnell® radar gun was used to measure ball speed (kph) after release. The throwing target was a chalked, 0.9144 m diameter black wood target, with the end of a tape measure affixed to the target center.

Test Task: The participant started 9.144 m away from the target and in front of the force platform from a natural standing position (Figure 4.2b) facing the target; when an aural signal sounded, a single-step drop-back pass (Figure 4.2b-c) was completed as quickly and accurately as possible to the target's center (Figure 4.2a).

Protocol: Rib protector conditions were tested in a counterbalanced order. Before all testing began, the bases of the spinal marker clusters and all markers not placed on the garment were affixed. Prior to throw task testing of any condition, the appropriate garment then was placed on the participant. The rods of the marker clusters were screwed into the bases and the remaining markers placed on the participant. For the hard-rib condition, the plastic insert was dipped in hot water, inserted into the rib protector 'pockets', and molded to the participant following manufacturer instructions. The participant then rated mobility and performance for the rib protector condition on a hard-copy 10 cm subjective visual analog scale (VAS) (Appendix C).

To warm up and prepare for the throwing task, participants completed a routine consisting of a short prescribed arm warmup, then a self-selected arm and throwing warm-up, followed by five practice throws with effort increasing from 50% to approximately 90% of maximal.

The participant then threw 10 acceptable trials. After each trial, throw error was measured as the distance between the center of the ball mark left on the target to the center of the target. The participant could see the ball mark. From visual observation, a trial was acceptable if the ipsilateral foot contacted only the force platform, and the ball hit the target, leaving a visible mark for error measurement.

After throws for a given rib protector condition were completed, the participant completed the VAS scales again. There was ~20 min. rest before starting the next rib protector condition's throwing trials. Once all conditions were tested, the participant then completed a form, first ranking all three rib protector conditions on mobility, comfort, protection against injury, performance, and overall best garment. Second, past history of rib protector use was obtained.

Data reduction: For generating a composite performance score ([2 x accuracy] + [ball speed]), throw error was converted into accuracy [cm]: (45 – throw error). Accuracy was weighted higher than ball speed as ball speed does not matter if the player receiving the ball does not catch it. The five trials for each rib protector condition that had the highest performance score were analyzed.

For kinematic data, the 'pelvic acceleration phase' was of interest and self-defined as the time from touchdown of the ipsilateral foot on the force plate (i.e., instant when VGRF > 10 N [80]) and ended at ball release. This phase was chosen because it includes the time interval when important axial trunk kinematics that contributes to ball speed and accuracy occur. VGRF signals were filtered (4th-order Butterworth low-pass digital filter, cutoff frequency = 300 Hz) prior to detecting VGRF foot contact time.

Three-dimensional coordinates of the markers were reconstructed using Vicon's Nexus software proprietary algorithm (v. 2.4) and low-pass filtered (4^{th} order Butterworth filter, cutoff frequency: 4 Hz).

For T8 and L3, each vertebra's spinous process was the origin of the local coordinate system, with axial rotation (+Z) towards the anterior direction (i.e., the target)[79]. The LT-AX-ROT angle was represented by the axial rotation position of T8 to L3 and calculated using the Cardan method (X-Y-Z sequence) and joint reference system of the T8 vertebra relative to the L3 vertebra. Peak LT-AX-ROT displacement occurring between the peak anterior and posterior angles was calculated to determine LT-AX-ROT range of motion. Peak LT-AX-ROT angular velocity and acceleration were calculated as indirect measures related to time to complete the throw, LT torque generation and lower trunk contribution to ball speed. Time to peak LT-AX-ROT acceleration was used to determine if timing of LT-AX-ROT kinematics is affected by rib protectors.

Performance-related variables, that included time to complete the throw (time from the aural cue to ball release), ball speed, and throw error, were used to determine if throwing performance was affected by rib protectors. For perception variables, the distances to the center of the participant's marks on each VAS mobility and performance scale was measured manually and scaled by the total scale length of 101 mm.

Data analysis: For the group data, for each rib protector condition, the average of the top five trials' values of a given variable was used for a participant's score. For intra-participant analyses, the individual trial data of each condition were used. For individual data and then group data, outliers were removed according to the Rule of Huge Error[81]. To test if a given rib protector did not have lower values compared to control, non-inferiority tests using the 95% CI of the difference score (**rib protector** value - **control** value) were conducted for each dependent variable (SPSS (v. 24 for Microsoft: SPSS Inc., Chicago, IL)[82]. The non-inferiority margin was set at one standard deviation of the control condition, as it was a conservative estimate of typical inter-individual variability of throwing and no prior values of minimal behavioral differences for these spinal motions exist.   Non-inferiority was tested as opposed to superiority because it was hypothesized that the effects of the rib protectors on the performance and kinematics magnitudes would be low enough to be within typical inter-participant variation and not behaviorally relevant. Statistical power (target of .8) was calculated for each non-inferiority test using the sample size, group means, standard deviation of the difference scores, non-inferiority margin, and sampling ratio[84].

In addition, corresponding individual participant non-inferiority tests were conducted to determine if participants were affected differently by the rib protectors. Aposteriori, Pearson-product correlations ($\alpha = .05$) between the trunk kinematic variables and performance variables were used to determine if LT-AX-ROT kinematics while wearing rib protectors were consistent with actual performance outcomes. Pre- and post-throwing perceptions were compared using difference-score 95% CI to determine if completing the throwing task improved participant perceptions of mobility and throw performance.

Results

No outliers were detected in individual or group outcomes. For the group outcomes, both rib protectors were shown to be non-inferior to the control condition for all performance (Figure 4.4a) and LT-AX-ROT (Figure 4.5a) variables. For the soft-rib condition, all difference-score confidence intervals included zero; 95% CI of four of the seven variables (ball speed, peak LT-AX-ROT displacement, peak LT-AX-ROT velocity, and peak LT-AX-ROT acceleration) were centered on or near zero. For the hard-rib condition, all confidence intervals included zero difference except for throw error. However, the 95% CI was still within the non-inferiority margin. For non-inferiority tests of the soft-rib protector, seven of the eleven variables had power above 0.8. Trunk axial displacement ($1\text{-}ß = 0.72$), throw error ($1\text{-}ß = 0.57$), perception of performance pre-throwing ($1\text{-}ß = 0.65$), and perception of performance after ($1\text{-}ß = 0.72$) had power < 0.8. For the hard-rib non-inferiority tests, all variables had power above 0.8 except throw error ($1\text{-}ß = 0.51$).

Neither rib protectors' VAS perception scores were non-inferior to control for performance (Figure 4.4b) nor mobility (Figure 4.5b) pre- or post-throw performance. The soft-rib non-inferiority VAS outcomes were inconclusive, as there were sizeable 95% CI widths. The hard-rib VAS was also inconclusive for performance perception. However, for mobility the hard-rib VAS was inferior to control VAS before and after completing the throws, and the 95% CI was lower than the soft-rib after completing the throws. No VAS score improved post-throwing.

Individually, hard rib had a lower VAS score than the control with all twelve participants before and after throwing for mobility and with six and eight participants before and after, respectively for performance. The soft-rib protector scored lower than the control for eight and ten participants for mobility before and after and four and nine participants for performance before and after, respectively.

For the individual participant LT-AX-ROT kinematic and throw performance non-inferiority test outcomes, the majority of participants had inconclusive outcomes (11/12) for both rib protectors in 50% or more variables. Four of the twelve participants had non-inferior test outcomes for at least one rib protector in 50% or more variables. No individuals had inferior outcomes for at least 50% of variables but eight of ten showed inferiority for at least one variable.

All correlations between LT-AX-ROT kinematic variables and ball speed, as well as between time to peak acceleration and throw time, were significant ($p = <.001$ to $.046$; $r = .151$ to $.444$) (Table 4.1). Time to peak angular acceleration x throw time exhibited a moderate correlation ($r = .444$, $p < .001$), while LT-AX-ROT displacement x ball speed ($r = .225$, $p = .003$), and LT-AX-ROT velocity x ball speed ($r = .260$, $p = .001$) exhibited weak, almost moderate, correlations.

Discussion

Overall, we hypothesized that, for the group outcomes, both rib protectors would be non-inferior to the control for the LT-AX-ROT kinematic and throw performance variables because any decrements resulting from increased lower trunk compression and mechanical restriction would be low enough in magnitude to cause a given rib protector difference score to remain within the typical inter-participant range of values for throwing. This hypothesis was supported for both rib protectors. In addition, it was also predicted that participants would perceive both rib protectors to be inferior to the control before completing the throwing task, with the hard rib protector receiving the lowest values due to perceived restrictions; but that after completing the throwing task, rib protector perceptions would be improved and therefore non-inferior to the control. Only the hypothesis for perceived mobility with the hard-rib before throwing was supported. Finally, our expectation that individuals' would have differing responses for performance and LT-AX-ROT variables with the rib protectors was supported. Though most of the testing outcomes were inconclusive, the remaining outcomes were mostly non-inferior though some results were inferior.

There were several limitations in this study. First, sample size was somewhat low due to the limited number of eligible competitive quarterbacks in the recruitment area. Among the eleven LT-AX-ROT kinematic, throw performance, and perception variables, sample size primarily influenced soft-rib non-inferiority test outcomes ($1-\beta = .8$ not met for four variables), as only one hard-rib variable (throw error, $1-\beta = .51$) was underpowered. Second, the ideal method for setting the non-inferiority margin (NIM) is to use previously reported behaviorally meaningful differences as the margin has a heavy influence on the test outcomes. However, these differences have not been reported for any of the measured variables in overhand football throwing. Therefore, an alternative method using the variability of the movement (1 SD) to set the NIM was employed. This is an acceptable method for setting NIMs if behaviorally meaningful differences are not available[83]. Third, non-inferiority outcomes for soft-rib relative to hard-rib may have been confounded due differences between the shirts. The garment properties (percentage of mesh vs solid material, seams, thickness) of each shirt were slightly different. The hard-rib compression shirt was also used for the sham condition. However, though the Young's modulus values for each shirt's material were different, the stiffness properties of the shirts were very similar on the garment level when tested (within 8% N/m). Finally, the markers used for LT-AX-ROT kinematics were placed on the skin and therefore could not capture lower trunk movement directly, as with any motion capture study. In addition, the motion artefact of marker clusters may have been greater than that of individual markers. However, the bases of the marker clusters were reinforced with Cover-roll® adhesive bandage to minimize motion and using a six-degrees of freedom pose estimation optimization method for computing the position and orientation of segments[85–88].

As predicted for group outcomes, all kinematic and performance variables for the soft-rib and hard-rib conditions were non-inferior to the control condition. The confidence intervals for both rib protectors fell within the non-inferiority range for all LT-AX-ROT kinematic and throw performance variables (Figure 4.5a and 4.6a).

For the kinematic variables, reasons for these outcomes are likely that trunk muscles are still able to produce the torque necessary to overcome the mechanical constrictions of the rib protectors. It is also possible that kinematic values may not be affected because the range of motion of the trunk during the participants' throws never reached an axial displacement great enough to deform the rib protectors to an extent that a large amount of torque is required. Additionally, a study by Roach and Lieberman[27] that looked at the effects of a hard, "nearly complete-restriction" torso brace (clavicle to the pelvis) on trunk axial rotation kinematics and performance variables during a fastball baseball pitch reported similar results. They found that wearing the brace showed no changes in peak power, angular velocity, and torque for trunk axial rotation, and time in the acceleration phase. Fleisig et al[29] has shown that overhand baseball throwing is shown to have faster upper torso rotation than football throwing so it would likely be more affected by restriction in the torso area. However, there are very few known studies assessing the overhand throw with equipment on for comparison. Therefore, the outcomes of Roach's study[27] and our study indicate that is likely that the rib protection padding in the lower rib area of each compression shirt does not hinder performance or the ability for a quarterback to move during completion of a throw and may also indicate that no matter the extent of restriction of rib protectors, these values would likely not change. As predicted, the variability from throw to throw likely overcame any small changes that the rib protectors may have caused making it not behaviorally significant. This is particularly apparent for peak LT-AX-ROT acceleration and time to peak LT-AX-ROT acceleration as they were not centered at zero but still fell within the non-inferiority range. It also may be possible that the lack of differences in trunk axial displacement for the soft-rib could have been due to insufficient power but it is not likely as the power was almost .8 ($1-\beta = .72$).

Performance outcomes were likely not affected for similar reasons as explained above. Particularly, if participants are already used to performing throws with limited trunk mobility, their performance values would also not be affected. However, there is some slight indication that the small effects that were experienced when wearing rib protectors may have translated to throw error and throw time, as their CIs were also not centered at zero. Roach et al also looked into the effect of wearing the brace on throw performance of the baseball pitchers in their study and found that there was no reduction in accuracy and only a slight, yet statistically significant drop in ball speed of ~3.6 kph, which is less than our group's control condition standard deviation. Fleisig's study[29] comparing football passing to baseball pitching also he found that the ball velocity of pitchers' throws (126 kph) was much greater than that of football players (75 kph) so it is likely that the drop in ball speed in Roach's study[27] is very similar, proportionally, to the negative end of the ball speed confidence interval in our study (95% CIs: soft- rib [-1.395, 1.395]; hard-rib [-1.151, .934]). Non-inferiority testing of throw error was also underpowered for the soft-rib (1-ß = 0.57) and hard-rib (1-ß = 0.51) so lack of difference may have arisen because of that. However, insufficient power usually leads to inconclusive results rather than non-inferiority.

All LT-AX-ROT kinematic variables were correlated to ball speed, and time to peak axial trunk acceleration was also correlated to throw time. Therefore, though LT-AX-ROT variables only represent mobility in a small percentage of the kinetic chain rotations that contribute to the throw performance[29], it is likely that the kinematic variables may partially indicate how quickly the quarterback can get the ball to their teammate in a game setting without getting the ball intercepted by opposing players. In addition, time to peak acceleration may also partially reflect how quickly the quarterback can throw the ball from the start of the play which decreases the possibility of them being tackled before the ball can be thrown.

Before throwing, the results were inconclusive for perception of performance for both rib protectors. For the soft-rib 1/3 of the participants scored the soft-rib the same as the control, another 1/3 scored it higher, and another 1/3 scored it lower. Similarly, half of the participants scored the hard-rib worse than the control and the other half scored it the same as the control. The high variability of these scores likely caused these inconclusive results. After throwing was complete, results were still inconclusive. However, it seems as if the scores leaned more toward inferior values as ¾ of the participants now scored the soft-rib lower than the control and 2/3 rated the hard-rib lower than the control. This may have been because, when qualitatively analyzing their feedback as they were throwing, it seemed as if many participants did not perform as well as they originally thought they would. This frustration may have led to lower ratings for the rib protectors after throwing.

When participants scored mobility before throwing, the hard-rib was perceived to be inferior to the control. However, a majority of the participants (8/12) and all of the participants perceived the soft-rib and hard-rib, respectively, to be worse than the controls. The extent that they though the hard-rib was worse than the control condition was much greater than they thought the soft-rib was. After throwing, all participants again though the hard-rib was worse than the control and the soft-rib was increased to 10/12 participants who thought it was worse. In addition to throwing, the participants also performed some stretching sequences that likely amplified their perceptions of mobility restriction causing some to score the rib protectors worse than previously. Though, as a group, participants perceived mobility to be reduced by the hard-rib condition before and after throwing, they did not also perceive the hard-rib to adversely affect performance. For mobility, the hard-rib likely performed so poorly due to the hardness of the protective insert that likely felt restrictive because it was molded to their bodies. The thickness of both rib protection areas were the same. However, the density of the hard-rib protection area was greater causing it to be heavier. Finally, the torque required to bend the hard-rib was much greater than the soft rib so it likely directly translated to participants' perceptions of not being able to rotate their trunk as well.

The prediction of improved perceptions after throwing was not supported for either rib protector. For both perception variables, there was an increase in how many participants (performance: + 5; mobility: + 2) scored the soft-rib protector as worse than the control from before throwing to after. Additionally, for the hard-rib there was an increase in the number of individuals that scored the protector lower for perception of performance (+ 2) but perception of mobility was already at the maximum amount so it could not increase.

Measured LT-AX-ROT kinematic variable outcomes did not follow their mobility perceptions. This incongruence between perceptions and actual mobility is likely indicative of what happens with American football athletes when wearing rib protection. These results show that their perceptions are usually not supported by empirical data. Though this has not yet been tested, if in the future data such as these can encourage players to wear more protection by convincing them that their performance will not be hindered, their confidence may in fact increase due to the feeling of having less risk of sustaining injury and may then lead to better performance[89].

Except for time to peak acceleration, individual participants did not all respond similarly to both rib protectors in trunk mobility and performance for all variables as predicted. Time to peak acceleration showed no inferior outcomes for either rib protector. Inferiority was most often seen in measurements of axial velocity and ball speed and, surprisingly, most often seen with the soft-rib condition.

In this study, inter-participant variation was likely so high because there was a large range of age/skill levels and not all participants currently played as quarterback. We surmise that shoulder and trunk musculature that contributes to throwing mechanics, as well as limited recent practice, may have decreased in those that have not maintained competitive play as a quarterback. Therefore, while those with stronger shoulder and trunk muscles and more practice with throwing could likely compensate for decreases in trunk rotation with greater shoulder torque, those individuals with decreased musculature may have been more affected by the addition of a rib protector. Various studies have also shown that individuals have differing responses to sports equipment due to varying biomechanics and morphological characteristics[31–35].

Most perception of performance ratings did not follow the same test outcomes as the individuals' actual performance and mobility results as only two participants with inferiority for axial velocity with soft-rib also rated the soft-rib the lowest for performance. No other perception measures seemed to follow trends in performance or mobility outcomes for either rib protector.

In summary, for the majority of quarterbacks, ranging from high school varsity to professional players, LT-AX-ROT kinematics and short-pass performance are not adversely affected by wearing a garment-style rib protector, regardless of protector hardness. Still, athletes perceived these garments to affect these variables. These results may be used to convince athletes to wear rib protectors if these protectors also are proven to be efficacious for preventing injury or attenuating rib/abdominal injury severity in American football quarterbacks. As there is little influence of rib protector hardness/stiffness or rib protector on performance or axial trunk kinematics, it is important that a given individual quarterback be able to try different rib protectors and select the one that he feels the most comfortable and confident wearing.

Acknowledgements

We thank the companies that provided the rib protector garments used in this study and our undergraduate researchers (alphabetically): Julia Dolgetta, Cristian Escalera, Morgan Green, Holly Kapella, Chandler Mulford, Haley Pierce, Jeremy Raiford, Christopher Suter, and James Tyson.

Table 4.1 Significant Pearson Product-Moment Correlations Between Lower Trunk Axial Rotation (LT-AX-ROT) Kinematic and Performance Variables

LT-AX-ROT Variable x Performance Variable	r	***p***
Displacement x Ball Speed	0.225	.003*
Velocity x Ball Speed	0.260	.001**
Acceleration x Ball Speed	0.151	.046*
Time to Max Acceleration x Ball Speed	0.177	.018*
Time to Max Acceleration x Throw Time	0.444	<.001**

Note. * = $p < .05$, ** = $p < .001$

Figure 4.1 — The rib protectors tested in this study: **(a)** soft-rib and **(b)** hard-rib. All logos were covered to avoid bias due to brand. Padding on the sternum and along the spine was made of a harm foam, not plastic like the rib inserts. The control condition consisted of the hard-rib compression shirt without the plastic inserts.

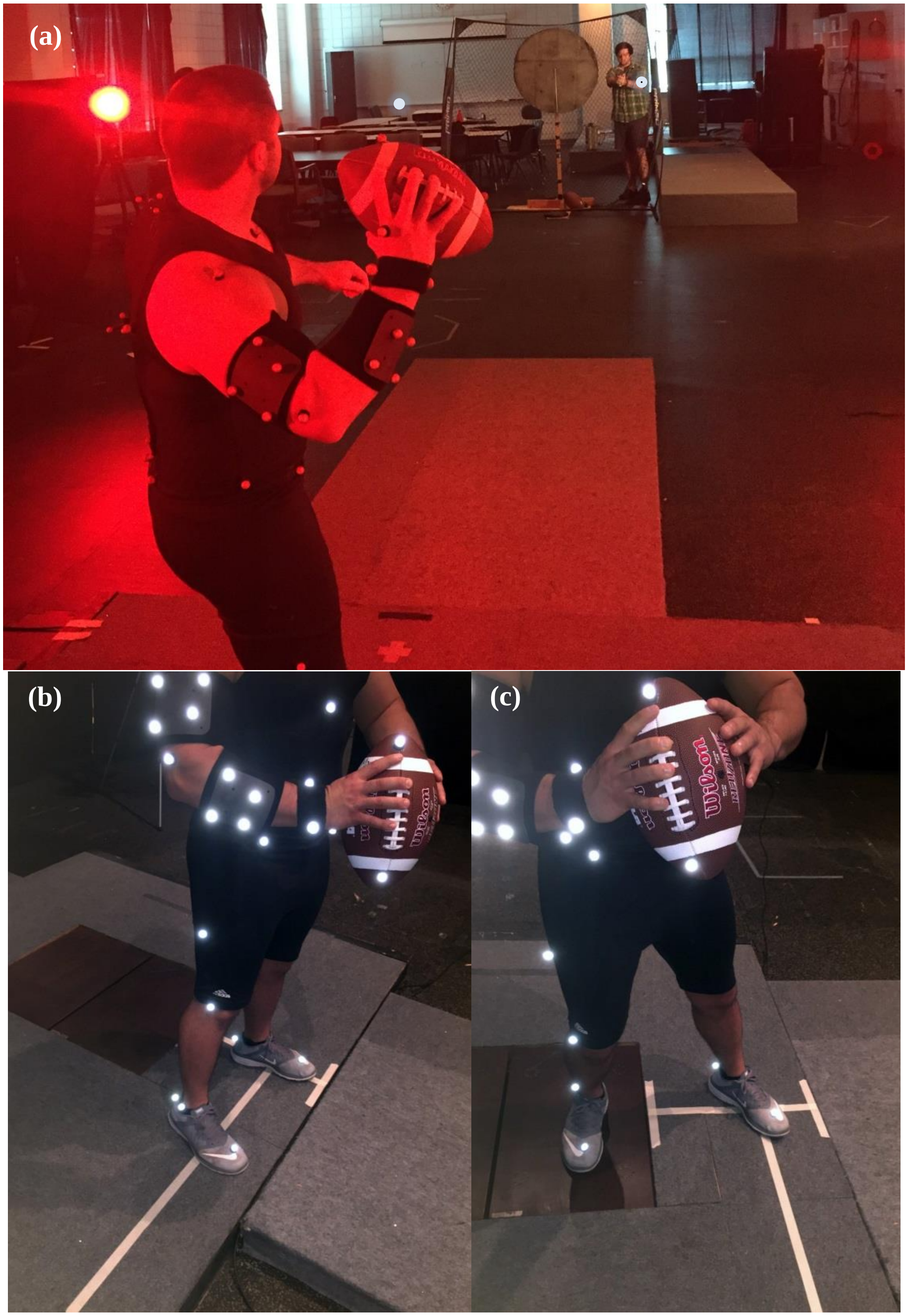

Figure 4.2 — Experimental setup and tasks. **(a)** The experimental setup for this study the target. The participant threw the ball to a target 9.144 m away while a researcher measured ball speed with a radar gun. **(b)** Starting position for the throwing task. **(c)** Position after single-step drop-back and before throw.

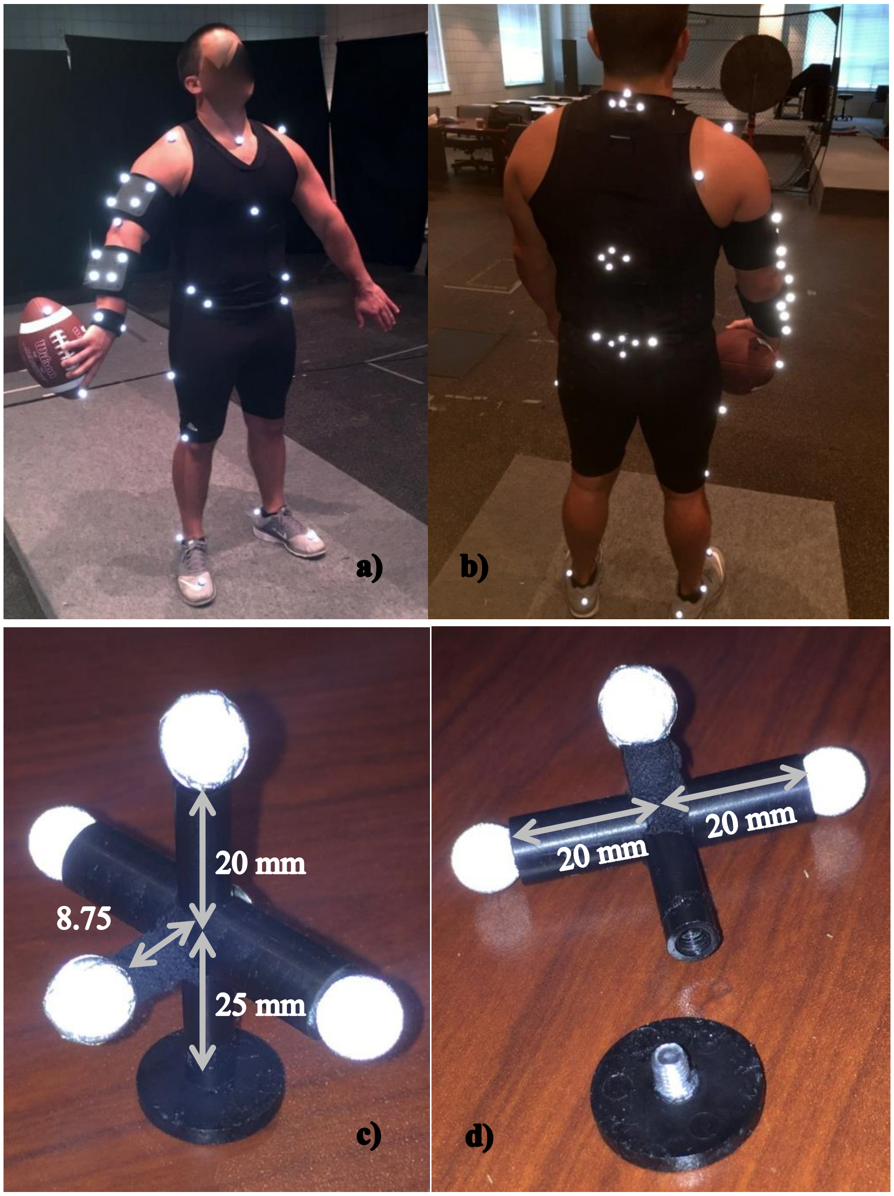

Figure 4.3 — Marker set. (a) Front view and (b) back view of the full marker set used for motion capture. Additional markers not used in this study were placed on the participant. (c) An assembled example spinal marker cluster set. (d) An unscrewed spinal marker cluster set. Marker sets placed on the C7, L3, and T8 vertebrae, were made of four 9.5 mm-diameter markers attached to a base consisting of a 6.6 mm-diameter vertical plastic rod crossed with a 9.7 mm-diameter horizontal plastic rod; a 3 mm-diameter screw, protruding from the 3 marker plane, covered with black tape; and a19.1 mm-diameter solid plastic base with a 4 mm-diameter screw projecting from it into the horizontal rod. The base was placed on the skin and fed through a small hole in the garment.

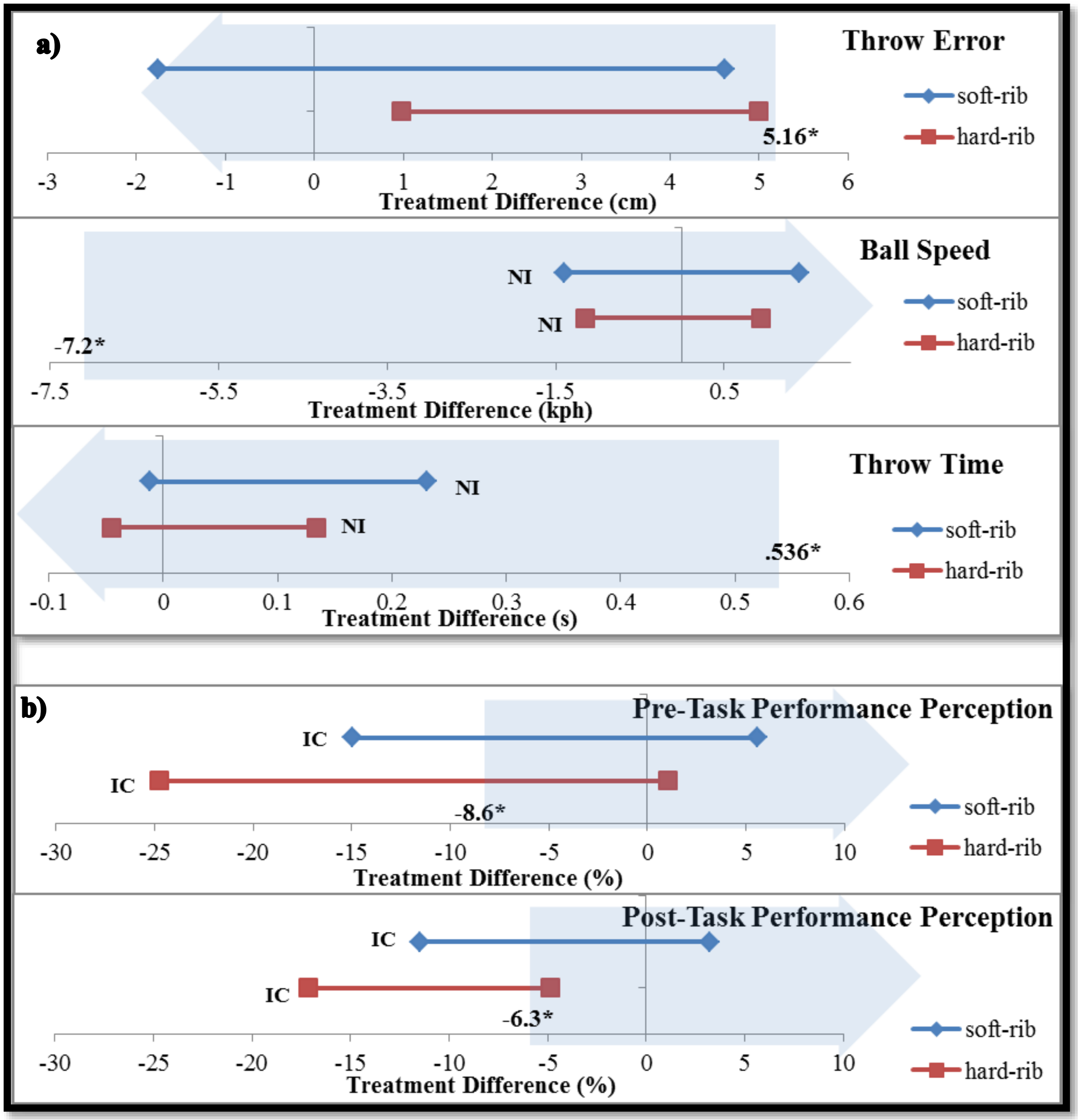

Figure 4.4 — Group performance non-inferiority testing. **(a)** Outcomes of group non-inferiority testing for performance variables showed non-inferiority for both rib protectors. **(b)** However, perception of performance was inconclusive at both time points. Thin lines show 95% CI of treatment difference (protector – no-rib) for each rib protector. Large arrow represents the non-inferior range: tail is boundary at the non-inferiority margin (value in bold text and *) and continues infinitely in the more 'favorable' difference direction. NI = non-inferior to NO-RIB and IC = inconclusive.

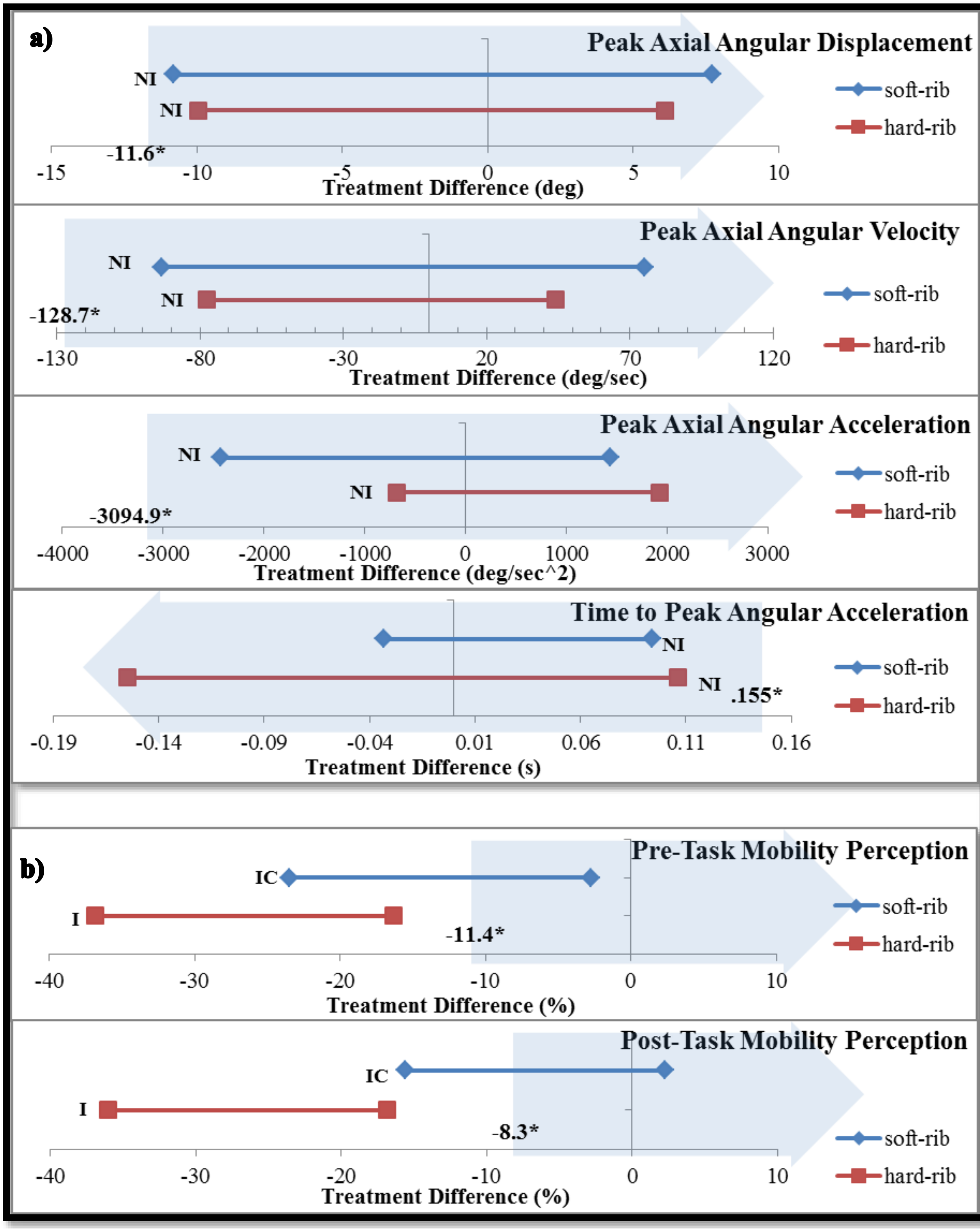

Figure 4.5 — Group mobility non-inferiority testing. **(a)** Outcomes of group non-inferiority testing for mobility variables showed non-inferiority for both rib protectors. **(b)** The hard-rib was inferior to the control in perception of mobility. Thin lines show 95% CI of treatment difference (protector – no-rib) for each rib protector. Large arrow represents the non-inferior range: tail is boundary at the non-inferiority margin (value in bold text and *) and continues infinitely in the more 'favorable' difference direction. NI = non-inferior to NO-RIB and IC = inconclusive.

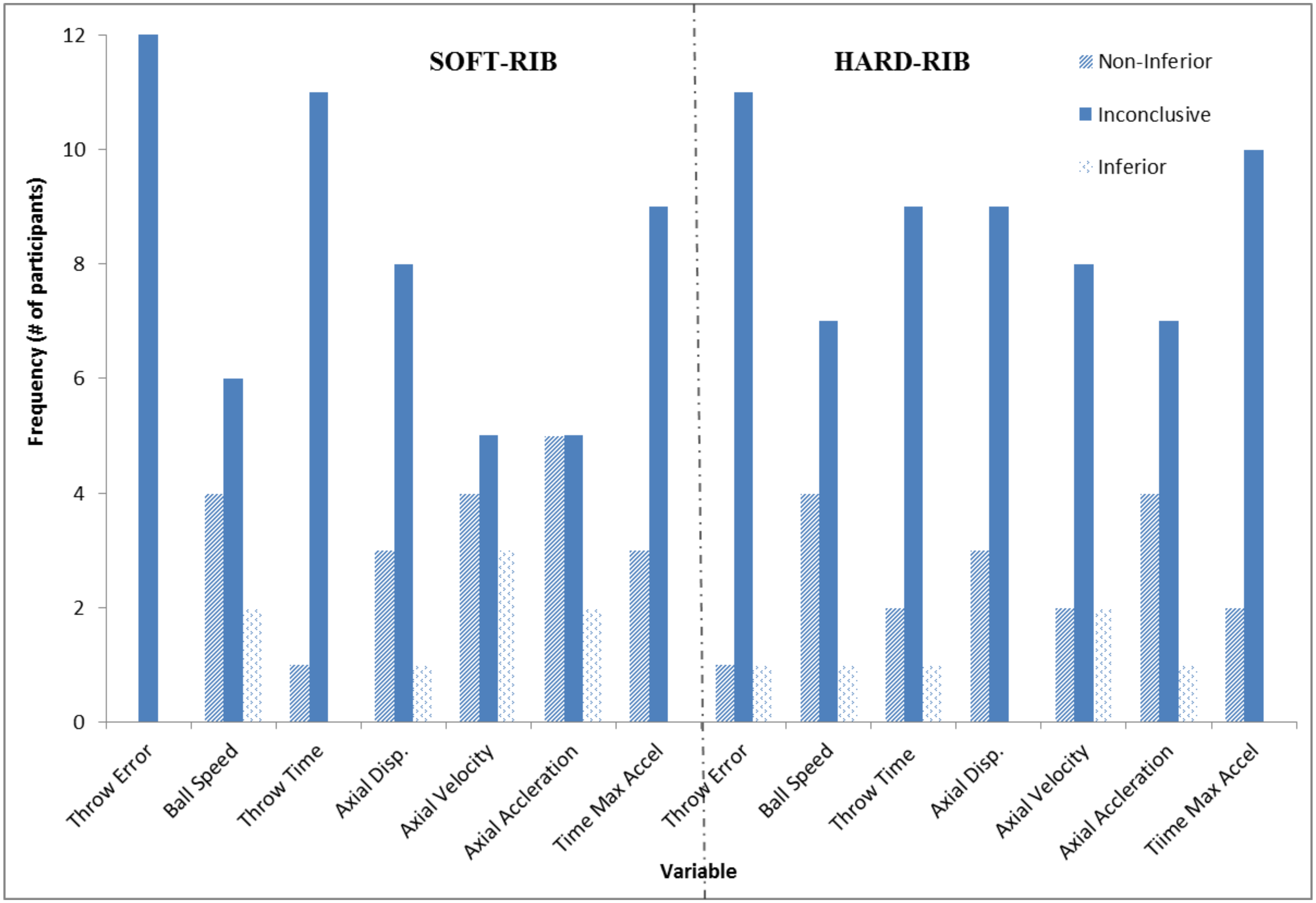

Figure 4.6 — Participant frequencies of individual participant non-inferiority testing outcomes showed that individual participants had varying responses to both the hard-rib and soft-rib. The soft-rib was inferior to the control in individuals more often than the hard-rib. However, the soft-rib was also non-inferior to the control in individuals more often than the hard-rib.

CHAPTER 5: Differences in trunk range of motion for various flexibility protocol types, particularly in quarterbacks wearing rib protectors[2]

[2] Walker, M. A., Samson, C. O., Simpson, K. J., Brown-Crowell, C. N., Foutz, T. To be submitted to *Medicine & Science in Sports & Exercise.*

Abstract

If injury-prevention rib protectors hinder the trunk mobility of quarterbacks, they are less likely to use them. The best method for measuring trunk flexibility to determine any potential mobility reduction, however, is unclear. The two purposes of this study were to first, determine which flexibility type (active-assisted, maximal speed, self-selected speed) exhibits the highest range of motion (ROM) for trunk lateral flexion and axial rotation for three rib protection conditions: control (compression shirt), hard-rib and soft-rib protectors, and second to determine if rib protectors affect trunk ROM. The lower-thoracic ROM for lateral flexion and axial rotation (7 digital cameras;120 fps) was calculated for each flexibility type and rib protector condition for 11 male quarterbacks. Repeated measures analysis of variance tests (flexibility type x rib protector condition) for each ROM direction demonstrated no interaction or rib protector main effect. Flexibility type exhibited the highest ROM value at self-selected speed for lateral flexion, and for axial rotation, maximal speed and active- assisted flexibility type. Using these highest ROM flexibility types, non-inferiority tests showed that neither rib protector was inferior to the control condition for lateral flexion, but were inconclusive for axial rotation. Therefore, it is likely that when there are mechanical restrictions due to anatomy, such as lateral-flexion, the self-selected protocol gives sufficient measures. However, when there is less restriction, protocols that utilize additional torque (trunk acceleration in maximal speed, external torque in active assisted) likely give higher values. Additionally, results of non-inferiority testing indicate that rib protectors likely do not affect the ROM needed to throw maximal long passes or other movements as performed by American football quarterbacks.

Keywords: non-inferiority testing, spinal ROM, active-assisted flexibility, methodology

Introduction

American football players sustain more injuries in practices and games than athletes in any other contact sport[90]. The risk of injury for all football players have been reported as high 8 per 100 athlete exposures (AE) in high school, 36 in college, and 65 in National Football League preseason games[6]. In the National Football League, from 2012 to 2014, quarterbacks and wide receivers in particular were injured at a rate of 42 per 1000 AE.

There may be an increasing danger of offensive players sustaining hits to the trunk area, particularly the ribs/abdominal region. Since 2010, rule changes have been made by collegiate and professional governing bodies that prevent tackling an offensive player above the shoulders or below the waist. Hence, a greater proportion of hits to a player likely occur to the ribs/abdominal region than previously. Only 86 total rib injuries were reported in the 11 seasons from 2000-2010, but 97 rib injuries were reported in the 2012 and 2013 seasons after the rule change was implemented. Moreover, these injuries can range from relatively minor, but painful injuries that occur fairly often, such as rib contusions, to more severe injuries, such as rib fractures and fatal solid organ injury[7–10]. Though solid organ injuries are rare, injuries to the spleen and kidneys, in particular, have been reported in football and other contact sports and have sometimes resulted in death[17,18].

Rib/abdominal protection could help to reduce the risk of sustaining these injuries and/or lessen the severity of injuries if worn[15,16]. No epidemiological studies have been published determining the efficacy of rib protectors, but for the two ‘garment’ rib protectors of interest in this study, we found that they have the potential for absorbing up to 43% of impact forces compared to wearing a compression shirt alone[91]. The two rib protector garments consisted of a compression shirt and varied due to the hardness with either hard plastic (**hard-rib**) or soft padding (**soft-rib**) in the lower rib area. Garment rib protectors tend to be thinner and lighter than traditional rib protectors, and thus, may be well suited to players in positions that require the most mobility and agility to directly score or prevent others from scoring points.

Quarterbacks' could benefit from the use of rib protectors if their ability to quickly and accurately move and throw a football in a game setting is not compromised. Quarterbacks are susceptible to injury of the ribs, as they handle the ball during almost every offensive play and their trunks are particularly vulnerable to hits when standing upright to complete a throw. Successful passes largely determine the outcome of games[92]; thus, rib protectors are less likely to be worn if they restrict the lower-trunk axial rotation and lateral flexion needed, thereby adversely affecting throw quality[29,63].

Therefore, because rib protector garments currently are not mandatory pieces of equipment, some players may choose not to wear them if they perceive that this additional equipment will hinder their performance. Researchers have shown that athletes will not wear prophylactic devices, such as ankle braces, headgear, and mouth guards, if there is discomfort and/or perceived impact on performance [19–21]. An unpublished study of these two rib protectors for trunk kinematics and performance of quarterbacks demonstrated during a maximal speed and effort long football pass and performance and mobility perceptions was conducted by Walker et al[91]. Most individuals perceived that a hard and/or soft rib protector would have a negative effect on mobility and performance. However, those perceptions often did not translate to actual decreased mobility and performance outcomes, as the rib protector garments did not perform inferiorly to a control compression shirt condition.

It is important to determine how rib protectors may affect trunk mobility in quarterbacks at the extreme ranges of motion, as more trunk motion than that demonstrated in the study above may be needed for other movements. Athletes then can make an informed decision on wearing rib protection and feel confident of their mobility and performance in a game setting.

To ensure that a trunk range of motion (ROM) value is truly the maximum ROM we need to determine the best protocol(s) to use for measurement. Most existing types of trunk ROM protocols may represent the type of ROM and utilize the speeds of movement a player require, but have the potential to produce different ROM outcomes. We have selected two of the most relevant active and one quasi-active flexibility type. The first two active protocols vary by speed: (self-selected: **SS**) and maximal (**MS**)[46]. Both result in similar ROM test values, however, a maximal-speed protocol movement can be less controlled[46,62]. The active-assisted (**AA**) protocol is a self-selected speed active movement followed by using a source of external force (e.g., person pulls/pushes against an object or a researcher applies force) to move the body segment further [58]. This type is of interest as it is partially passive and may utilize the mechanisms that cause passive stretching to be more effective in getting to higher ranges of motion[36]. In addition, as the Institutional Review Board would not allow contact to occur in this research study, this flexibility protocol would be the closest to replicating contact in a game setting. However, we do not know how this protocol actually compares to the others in trunk

ROM measurement. In addition, all, to our knowledge, have been focused on assessing the participants' flexibility, not the potential mobility restriction of protective equipment so we do not know which protocol will work best for that purpose.

Flexibility values could be different among these three protocols because of the tissue mechanics of and mechanoreceptors within the trunk. While wearing a rib protector, the person's trunk flexibility, and the rib protector's 'flexibility' (i.e., mechanical properties), and potentially, consequences of potential increased mechanoreceptor input influence ROM[93]. Because of the differences in speed and the presence or absence of passive stretch of the participant's trunk muscles during these protocols, there are differences in mechanical properties (e.g. magnitude and rate of force applied to soft tissue and the somatosensory receptors) causing differing viscoelastic responses of the tissues and the exact receptors triggered. This will lead to effects that will either enhance or inhibit ROM. In addition, the rib protector materials are also viscoelastic and have their own mechanical loading properties. The hard-rib garment likely does not allow much deformation of the insert but allows trunk movement due to the stretch of the shirt. The soft-rib would allow some stretch of the shirt as well as the protector padding. For each, the stretching properties of the entire rib protector garment as the participant goes through a range of motion causes a resistive force. The participant's muscles then have to create more torque to overcome that resistance. Therefore, the muscle spindles and Golgi tendon organs in the soft tissues would likely be activated in the antagonist muscles earlier and flexibility may be reduced. Altogether, the viscoelastic properties of the participant's soft tissue and the mechanical properties of the rib protectors as well as the flexibility protocol's movement mechanisms could influence somatosensory input, muscle force generated, mechanical restriction of trunk motion, and therefore lead to complex effects on trunk flexibility.

Therefore, it is important to test these protocols to determine which is best to measure trunk ROM. Though a SS speed may potentially be safer than a MS protocol, due to more control of trunk motion, [46], AA and MS types may be more comparable to what quarterbacks may experience in a game situation. Active-assisted movement is the closest to mimicking contact between another player and a quarterback in the midst of a throw and the maximal speed type would be similar to the fastest and farthest throw that they may need to perform.

Hence, the purposes of this study were to determine for quarterbacks: (1) the flexibility protocol that produces the maximum values for lower-trunk maximal axial rotation and lateral flexion ROM while wearing rib protectors and (2) the effects of hard- and soft-rib protectors on the lower trunk ROMs. We hypothesized that the ROM magnitudes (from lowest to highest) would be the MS, SS, and AA tasks, respectively, for all rib protectors during axial rotation and lateral flexion of the lower trunk. This was expected because moving at maximal speed likely activates the somatosensory receptors (Golgi tendon organs and muscle spindles) of the trunk sooner, and causes the muscles, tendons, and ligaments of the trunk to have greater stiffness due to the rate that they are being stretched. The SS and the AA tasks should allow the participant to rotate without activating these receptors as early and at a slower rate of stretch than the MS task but the AA task would also allow slightly more stretch at the end of the ROM due to the additional stretch that is achieved as greater changes in force are required to activate muscle spindles with passive stretching than active stretching[30].

We hypothesized that the soft-rib would have non-inferior ROM and the hard-rib would have inferior ROM to wearing a compression shirt with no rib protection (control). This was because muscles in the trunk would have to produce more torque to overcome the stiffness of the hard-rib, and would cause activation of the muscle spindles earlier. However, the soft-rib will be flexible enough to not affect these values significantly.

Methods

A convenience sample of 11 males (age: 24.1 ± 4.1 y, height: 180.35 ± 4.9 cm, mass: 90.20 ± 10.19 kg) with competitive quarterback experience (n = 6 high school varsity, 3 collegiate, 2 professional level) took part in this study. Participants were required to be physically active and have no history of spinal conditions or medical treatment for those conditions. Institutional approval of protocol and informed consent was obtained before the study was conducted.

Each of three rib protector conditions (soft- and hard-rib protectors and control) were tested during three flexibility-type protocols (SS, MS, AA) for axial rotation and lateral flexion in a quasi-counterbalanced order. The soft-rib and the hard-rib (Figure 5.1) each contained protection to cover the ribs and the lower spine within a sleeveless compression shirt. The soft-rib's padding was non-removable and contained individual hexagon-shaped foam pieces. The hard-rib contained moldable inserts with hard plastic on the outside and a thin foam layer against the ribs. Each plastic insert was a honeycomb pattern (with hollow centers). The control condition consisted of the same compression shirt used for the hard-rib condition but without the inserts. Both compression shirts consisted of knitted spandex material with mesh in various areas throughout the shirt (Figure 5.1). The compression shirts for the soft-rib and hard-rib/control were 0.71 and

0.44 mm thick, respectively. Overall stiffness, obtained through informal garment level stiffness testing, for hard and soft-rib garments and control were 101.27 N/m, 108.40 N/m, and 75.22 N/m, respectively.

Instrumentation: To obtain lower-trunk ROM during flexibility tasks, spatial locations of the reflective markers were captured (240 fps) using a 7-camera motion capture system (MX-40™, Vicon Motion Systems Ltd., UK). Two marker cluster sets were placed on the T8 and L3 spinous processes (Figure 5.2) and used later to calculate lower thoracic relative angles about the axial and anteroposterior axes. For each spinal marker cluster, the base was placed directly on the skin and fed through a 4mm diameter hole in the compression shirt portion of the rib protector garment to meet the rod of the marker cluster where the rod was screwed into place. The locations for all markers that were placed on the rib protector garments were marked on the participant prior to marker placement to ensure that the marker locations were the same for each rib protector condition.

Test tasks: For each flexibility type, a lateral flexion and an axial rotation task was performed. For the SS and MS flexibility tasks, the participant rotated as far as possible with their elbows flexed at their sides, while minimizing out-of-plane movements. SS was performed at a natural, self-selected pace and MS was performed as quickly as possible while maintaining body control. For the axial rotation task, the participant was seated on a platform with the legs extended forward and strapped down, with knees slightly flexed (Figure 5.3a). The participant actively turned to the left, the right, then to the left again before returning to the neutral position. For lateral flexion, from a standing position, with feet about shoulder width apart, the participant, bent and reached to the left, right, left, and then returned to the neutral position. To complete the AA flexibility tasks [58], the participant completed the same movements described for the SS type with some slight additions as shown in Figure 5.3c-d. During axial rotation, when reaching an end of the active ROM, the hands were placed flat on the ground on the side of rotation and pushed parallel to the surface to increase rotation of the trunk without causing discomfort, as shown in Figure 5.3a-b. For lateral flexion, for a given bending direction, after achieving highest active lateral flexion position, the participant then grasped a vertical pole with a 13 kg weight base to create additional, passive lateral flexion. Each combination of direction and flexibility type was repeated three times for each condition.

Protocol: Before all testing began, the bases of the spinal marker clusters and all other markers not placed on the rib protector garment were affixed to the participant. Prior to the flexibility tasks for each condition, the garment being tested was placed on the participant and the marker clusters were screwed into the bases. In addition, all other markers were placed on the participant. For the hard-rib condition, the plastic inserts were dipped into hot water, placed into the pockets of the garment, and molded to the participant's body. For each rib protector condition, all participants started off with a static calibration trial. The participant warmed up by walking and/or jogging 2-5 minutes on a treadmill at a self-selected pace; then lightly stretching the back three times in each plane for 5 seconds each. For each flexibility task, the participant practiced then performed the flexibility tasks in a quasi-counterbalanced order with 10 s of rest between each trial.

Data reduction: The raw two-dimensional marker locations from each camera were reconstructed into 3-D coordinates using the Vicon Nexus software proprietary algorithm

(v. 2.4), filtered (4th order Butterworth low-pass filter, cutoff frequency = 2 Hz); then optimized using six-degrees of freedom pose estimation for computing the position and orientation of segments, and processed using Visual 3D software (Visual 3D; v. 6; C-Motion Inc.). The local coordinate systems for T8 and the L3 vertebrae were oriented with the origin on the spinous process, with axial rotation (+Z: twisting counter-clockwise to the left) and lateral flexion (+X: bending to the right side)[79]. The angles of T8 relative to L3 (peak right and left axial rotation and peak right and left lateral flexion) were calculated for a joint reference system of the T8 vertebra relative to the L3 vertebra using Cardan rotation sequence of X-Y-Z in Visual 3D. For each trial, the range of motion (ROM) about the axial and lateral flexion axes were calculated as the maximum displacement displayed between any two consecutive peak angles.

SPSS (Version 24 for Microsoft: SPSS Inc., Chicago, IL)[82] was used for all statistical testing. The mean max displacement was used for each test for each variable. For each variable, outliers were removed according to the Rule of Huge Error among the group[81]. For axial rotation and lateral flexion separately, a 3 Rib Protector x 3 Flexibility Type repeated measures (RM) analysis of variance (ANOVA) ($\alpha = .05$) was conducted to answer two questions: Do all rib protector conditions exhibit the highest ROM displacement during the same flexibility type? Which flexibility type, if any, displays the highest displacement? The answers to these questions were used to identify an appropriate flexibility type to use for subsequent non-inferiority of each rib protector compared to control. If the answers were false due to significant interaction, the flexibility type that had the highest control value was used. Otherwise, if flexibility type main effect was significant, then the flexibility type exhibiting the greatest value was used, as identified by Fisher's LSD post-hoc testing. If multiple flexibility types had the highest mean, the flexibility type deemed most behaviorally applicable to football quarterbacks would be chosen. The main effect of rib protector was anticipated to be nonsignificant and not useful, as testing the hypothesis of rib protectors being non-inferior to the control requires use of a different approach. Mauchly's test for sphericity was conducted and *p* was adjusted as necessary.

Subsequently, for the trunk ROM displacements using the corresponding flexibility type for each ROM direction, a non-inferiority test using a 95% confidence interval (CI) was conducted for each rib protector using the difference score (rib protector value - control value). Non-inferiority was tested as opposed to superiority because it was predicted that each rib protector would demonstrate ROM's similar to those exhibited when not wearing a protector. The non-inferiority margin (NIM) for each flexibility direction was set at one standard deviation of the control condition of the tested flexibility type. This NIM criterion was selected as it is representative of the variability of the flexibility type that would be measured while not wearing a rib protector garment. It is unknown what a clinical meaningful difference is for trunk ROM, as it has not been reported in the literature. However, choosing an NIM value that represents the minimum detectable change above the majority of the group's variability is an acceptable way of determining the NIM[83]. Statistical power was calculated for each non-inferiority test using the method described by Chow, Wang, & Shao[84]. An acceptable power value was .8.

Results

The interactions from the RM-ANOVA (flexibility type [AA, MS, SS] x rib protector [soft-rib, hard-rib, control]) for both ROM directions were not significant (Figure 5.4). Flexibility type was significant for lateral flexion ($F(2, 20) = 5.389$, p = .013, $1-\beta = .78$) , but not axial rotation displacement ($F(2, 20) = 2.230$, p = .134, $1-\beta$ = .4). For lateral flexion, the ROM displacement was highest for SS, as it was greater (p = .009) than MS by approximately 7° although only insignificantly greater than AA by 2.4° ($p \geqq .873$). For axial rotation displacement, AA and MS conditions exhibited a similar mean of 62° (<0.15 deg difference). Therefore, for axial rotation and lateral flexion non-inferiority testing, SS and MS, respectively, were used.

Non-inferiority testing are shown in Figure 5.5. For lateral flexion, the soft-rib (NIM: -13.52°; 95% CI: [-9.1, 8.1]; p = .874; $1-\beta = .81$, $\alpha = .05$; Chow et al[84]) and hard-rib (NIM: -13.52°; 95% CI: [-11.0, 2.412], p = .288; $1-\beta = .90$, $\alpha = .05$; Chow et al[84]) were non-inferior to the control condition (Figure 5.5). For axial rotation, non-inferiority testing was inconclusive for soft- rib (NIM: -14.88°; 95% CI: [-18.5, 12.5], p = .316; $1-\beta = .81$, $\alpha = .05$; Chow et al[84]) and hard-rib (NIM: -14.88°; 95% CI: [-27.0, 6.9], p = .347; $1-\beta = .90$, $\alpha = .05$; Chow et al[84]).

Discussion

This study, as best we know, was the first to test differences between several common flexibility types used for measuring trunk ROM with motion capture to test the effect of rib protector garments or other lower-trunk injury-prevention devices on flexibility. We predicted that for all rib protector conditions and both ROM directions, lower-trunk ROM would be greatest for the AA; followed by the active SS speed; and lowest for the active MS flexibility type. These hypotheses were only partially supported. The only hypothesis supported was that for a given ROM direction, there was one flexibility type that demonstrated greater values regardless of rib protector condition. AA had greatest ROM but that was equal to values of another type and only for a particular direction. Otherwise, the rank of ROM values was not supported and was not the same for both ROM directions. Finally, it was predicted that for the selected flexibility protocols in each direction, the soft-rib and hard-rib would be non-inferior and inferior to the control, respectively. This was partly supported as the soft-rib was non-inferior to the control for lateral flexion. No other parts of this hypothesis were supported.

The first prediction that the AA protocol would give the highest ROM values, followed by the SS protocol, and finally the MS protocol regardless of rib protector condition or direction was not supported, as there was not one flexibility type that exhibited superior values for both ROM directions. Lateral flexion and axial rotation directions had differing results. For lateral flexion, the SS protocol demonstrated the greatest ROM followed closely by the AA, and finally MS, which was significantly less than SS. For axial rotation, MS and AA revealed the highest values and the SS protocol had the lowest.

A possible reason that the AA protocol may have demonstrated a non-significantly lesser (2.4°) ROM than AA, for lateral flexion, was because the facet joints and the intertransverse ligaments within the spine mechanically restrict the amount of lateral flexion preventing additional displacement during the passive stretching phase if already reached their max ROM. This would cause both the AA and SS protocols to be fairly similar. That slightly greater value for the SS may have come from more familiarity with the movement, as most stretching is done at the person's own pace. However, the difference was not significant. The MS likely gave the lowest values because of activation of the stretch reflex by the muscle spindles due to rapid stretch of the antagonist muscles through the smaller range of motion[94].

For axial rotation, the MS and AA protocols demonstrated the best values and the SS speed had the lowest values. The two directions may have had incongruent results because the articular constrictions in lateral flexion are not present during axial rotation. Therefore, the AA and MS protocols could contribute to the additional rotation of the vertebrae. It is likely that the muscles could not rotate the trunk fast enough to fully activate the muscle spindles or the Golgi tendon organs through the larger range of motion so the additional momentum of the MS flexibility task only added to the ROM[95,96]. In addition, due to increased proprioception caused by the presence of the compression shirt in the control and other rib-protector conditions, the transmission of mechanical stimuli may have been interrupted[93].

McIntyre, Glover, and Reynolds compared active MS and SS speed lower trunk ROM in all directions (axial rotation, lateral flexion, flexion and extension) and found that the SS speed protocol produced approximately 85% of maximal values for axial rotation and 95% of maximal for lateral flexion[62]. This is consistent with what we found for axial rotation (88%) but different than what we found for lateral flexion (115%). However, the differences in their study for lateral flexion particularly, as they state, are likely not clinically significant.

For lateral flexion, as the SS performed the best, it is likely best for clinicians and athletic trainers to continue to measure flexibility actively at the participants pace. However, for axial rotation, though the results were not significant, AA at the participant's pace and MS performed the best indicating that the maximum ROM likely cannot be reached with the muscles alone and need outside aids such as high momentum (MS) or an applied torque (AA) to get there. When measuring changes in axial trunk ROM while wearing rib protectors, MS measurements seem to be the more applicable of the two flexibility types, as they mimic game movements, so those should be used.

The predictions that for both movement directions, trunk ROM of the participants would be non-inferior to the control while wearing the soft-rib but inferior while wearing the hard-rib were partially supported. Both rib protectors were non-inferior to the control with lateral flexion, indicating that rib protectors do not hinder mobility of the lower trunk in this motion plane. This is likely because as expected, the individual pieces of the soft-rib padding in conjunction with the compression shirt within the garment allowed enough stretch to not interfere with ROM of the individuals. It was initially predicted that the hard-rib, as it is much stiffer and does not allow any stretch, would stop the trunk from rotating past a certain point. However, it is likely that the compression shirt allowed stretch and therefore further rotation throughout the entire ROM as well.

The results for axial rotation were inconclusive as the difference CIs overlapped the non-inferior and inferior ranges. This is likely, in part, because the velocity of the trunk during the MS protocol was not controlled. The participants were instructed to rotate the trunk as fast as they could but that maximal angular velocity could have varied from person to person. Therefore the momentum and torque applied to the trunk contributing to the end ROM displacements in the transverse plane would not have been consistent and there would be more inter-participant variability. This may have caused the difference CIs for axial rotation to be relatively wide, thus causing inconclusive results. The difference CIs were centered within the non-inferiority range for the hard-rib and soft-rib conditions, indicating that they may perform non-inferiorly to the control within a more homogenous sample.

In support of this statement is a study by Walker, Samson, and Simpson [91]. For lower trunk axial displacement demonstrated during a maximal effort throw, using the same rib protector conditions as this study, they also found that the hard-rib and soft-rib performed non-inferiorly to control. Additionally, a study by Roach and Lieberman found that for baseball pitchers, axial trunk ROM did not change with the presence of a rigid, full-torso brace[27].

Although not proven here, there may be a potential optimal range of flexibility that a quarterback may want to have in a game setting. The trunk needs to be able to rotate enough to effectively throw a ball quickly, accurately and, at times, as far as possible. However, some resistance may be helpful to prevent excessive trunk rotation when tackled.

One limitation of this study was the sample size for the RM ANOVA, leading to insufficient statistical power ($1-\beta = .4-.78$). Another limitation was the lack of known behaviorally-relevant differences to set NIM, although our chosen method is an acceptable alternative[83]. Finally, a third limitation was that the compression shirt used in the control and hard-rib conditions was different than the one used in the soft-rib condition. However, the hard-rib/control compression shirt provided almost the same compression force (within 8%) as the soft-rib compression shirt during static garment stiffness tests (Appendix F). Still, compression during movement is unknown. Though the hard-rib/control had a larger Young's Modulus (4.878 x 10^{-4} GPa) than the soft rib (2.401 x 10^{-4} GPa), it was also thinner (.41 vs .64 mm) making the overall stiffness roughly the same (Appendix G).

In conclusion, if selecting a ROM protocol among these active type flexibility protocols, self-selected speed and maximal speed may produce the highest lateral flexion and axial rotation ROM, respectively, and can be used to test the influence of rib protectors and potentially other sports equipment on ROM of the thoraco-lumbar trunk area.

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Conflict of Interest

Several companies were asked to volunteer their product for inclusion in this study. No companies had any investment in this study; they only contributed rib protectors and do not directly benefit from any results in this study, as we do not identify the rib protectors by company. The results of the present study do not constitute endorsement by the American College of Sports Medicine. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Figure 5.1 — The rib protectors tested in this study: **(a)** soft-rib and **(b)** hard-rib. All logos were covered to avoid bias due to brand. The control condition consisted of the hard-rib compression shirt without the plastic inserts.

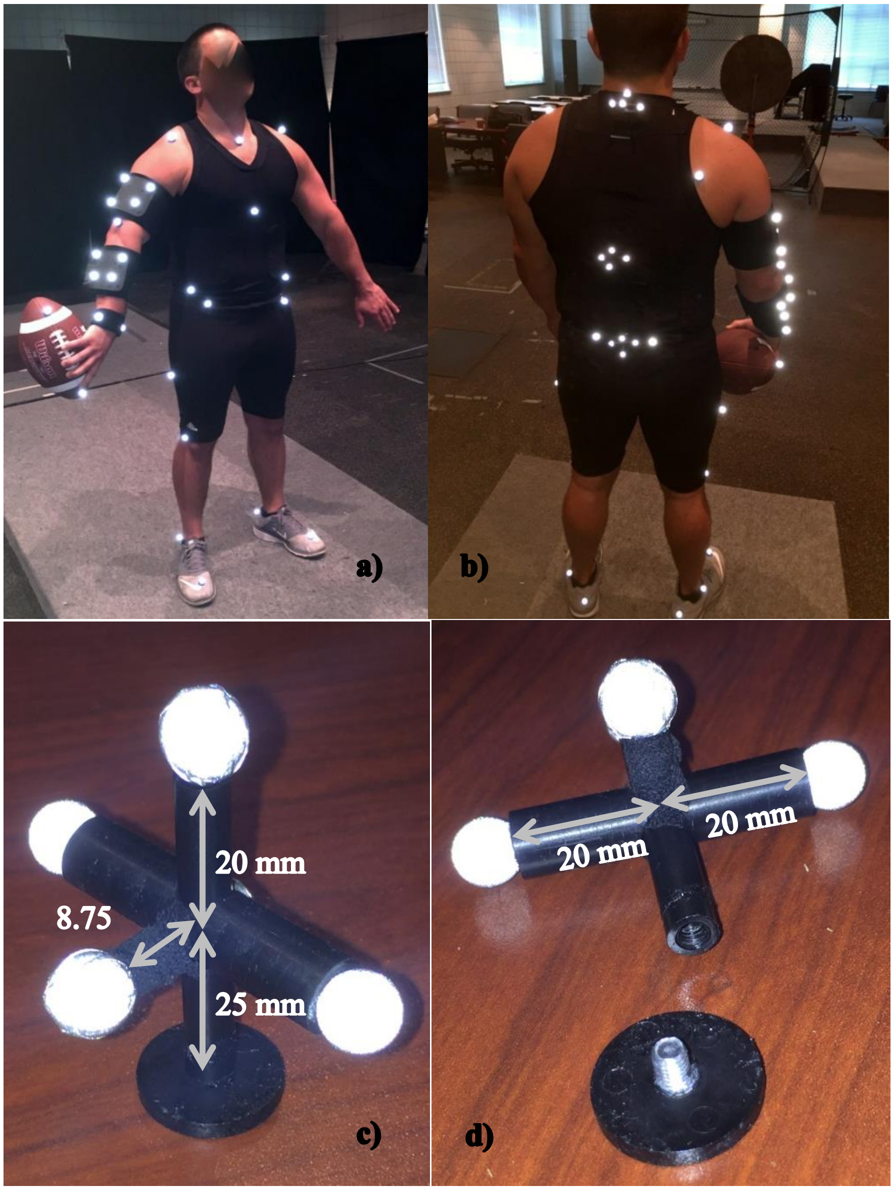

Figure 5.2 — Marker set. **(a)** Front view **(b)** and back view of the full marker set used for motion capture. **(c)** An assembled example spinal marker cluster set. **(d)** An unscrewed spinal marker cluster set. Marker sets placed on the C7, L3, and T8 vertebrae, were made of four 9.5 mm-diameter markers attached to a base consisting of a 6.6 mm-diameter vertical plastic rod crossed with a 9.7 mm-diameter horizontal plastic rod; a 3 mm-diameter screw, protruding from the 3 marker plane, covered with black tape; and a19.1 mm-diameter solid plastic base with a 4 mm-diameter screw projecting from it into the horizontal rod. The base was placed on the skin and fed through a small hole in the garment.

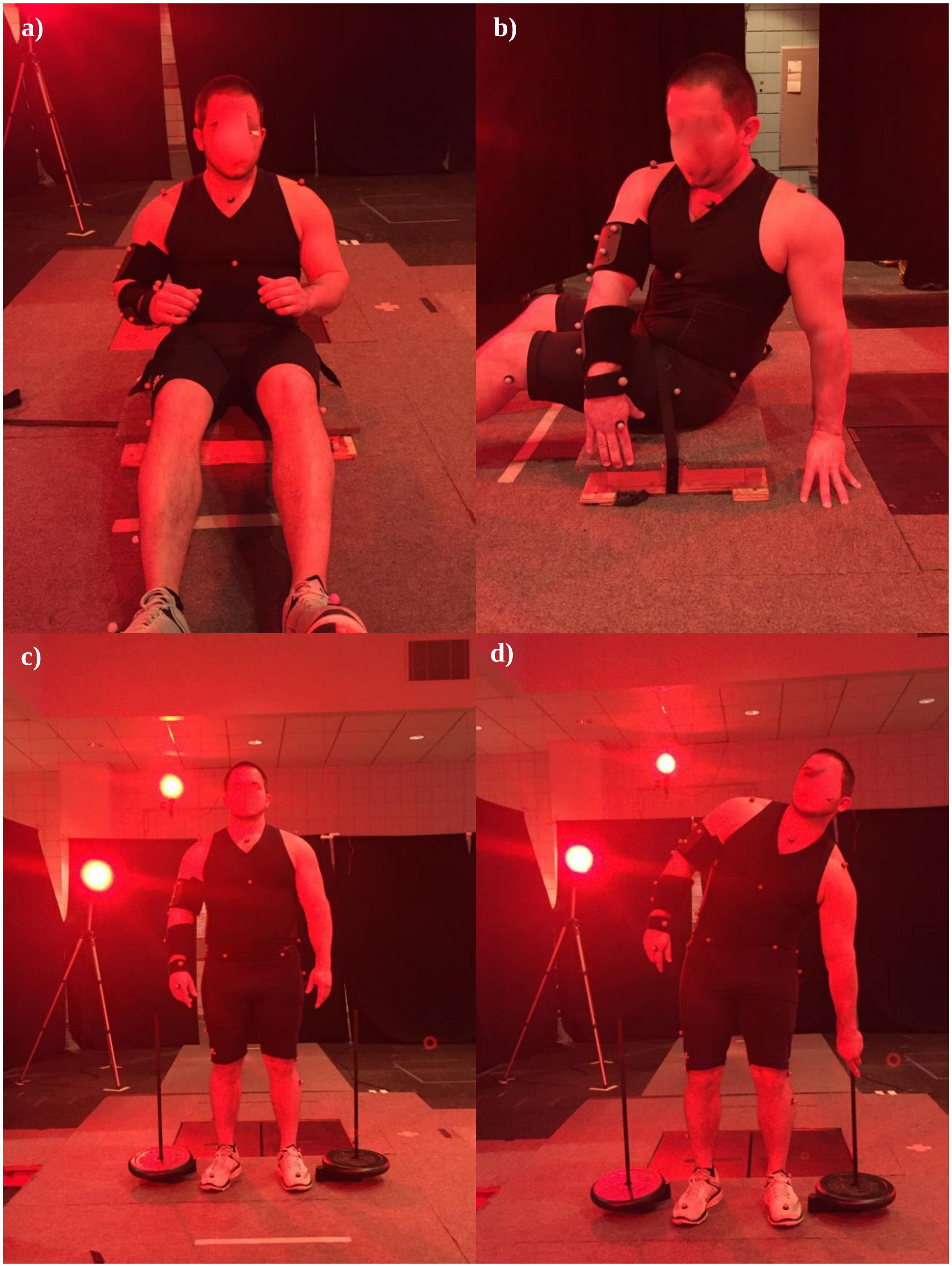

Figure 5.3 — Active-assisted flexibility protocol. **(a)** Starting position of the axial rotation active-assisted (AA) flexibility type. **(b)** Passive portion of the axial rotation AA type. **(c)** Starting position of the lateral flexion AA flexibility type. **(d)** Passive portion of the lateral flexion AA type.

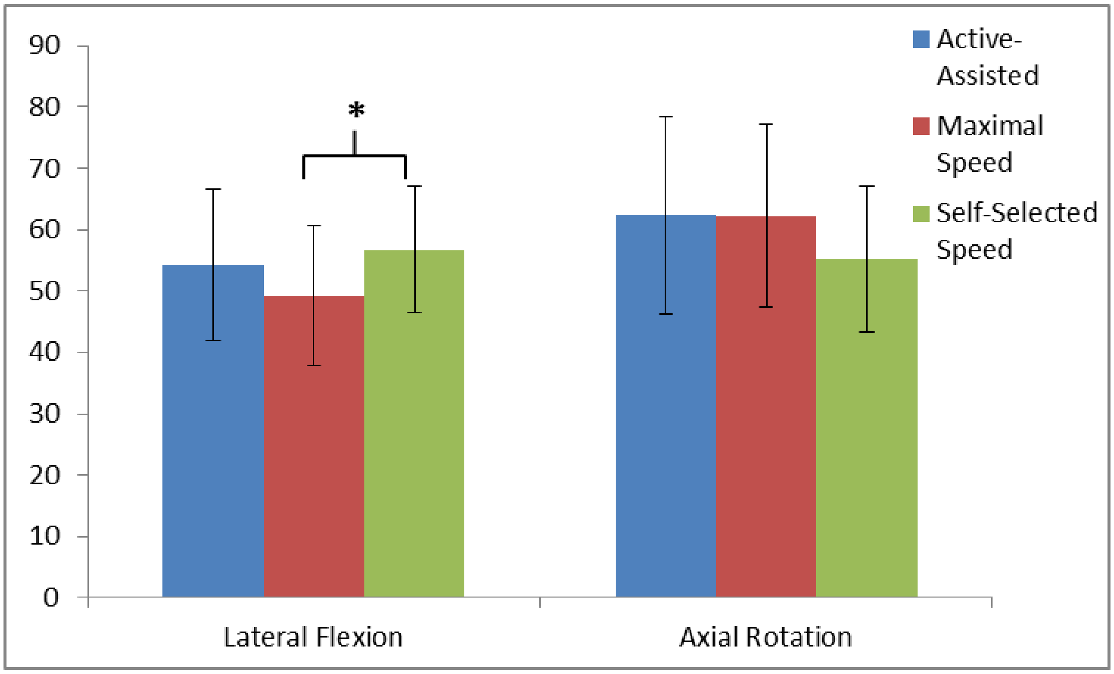

Figure 5.4 — Lower trunk ROM for each flexibility type in each direction. Error bars indicate plus and minus one standard deviation. * indicates a significant difference ($p < .05$).

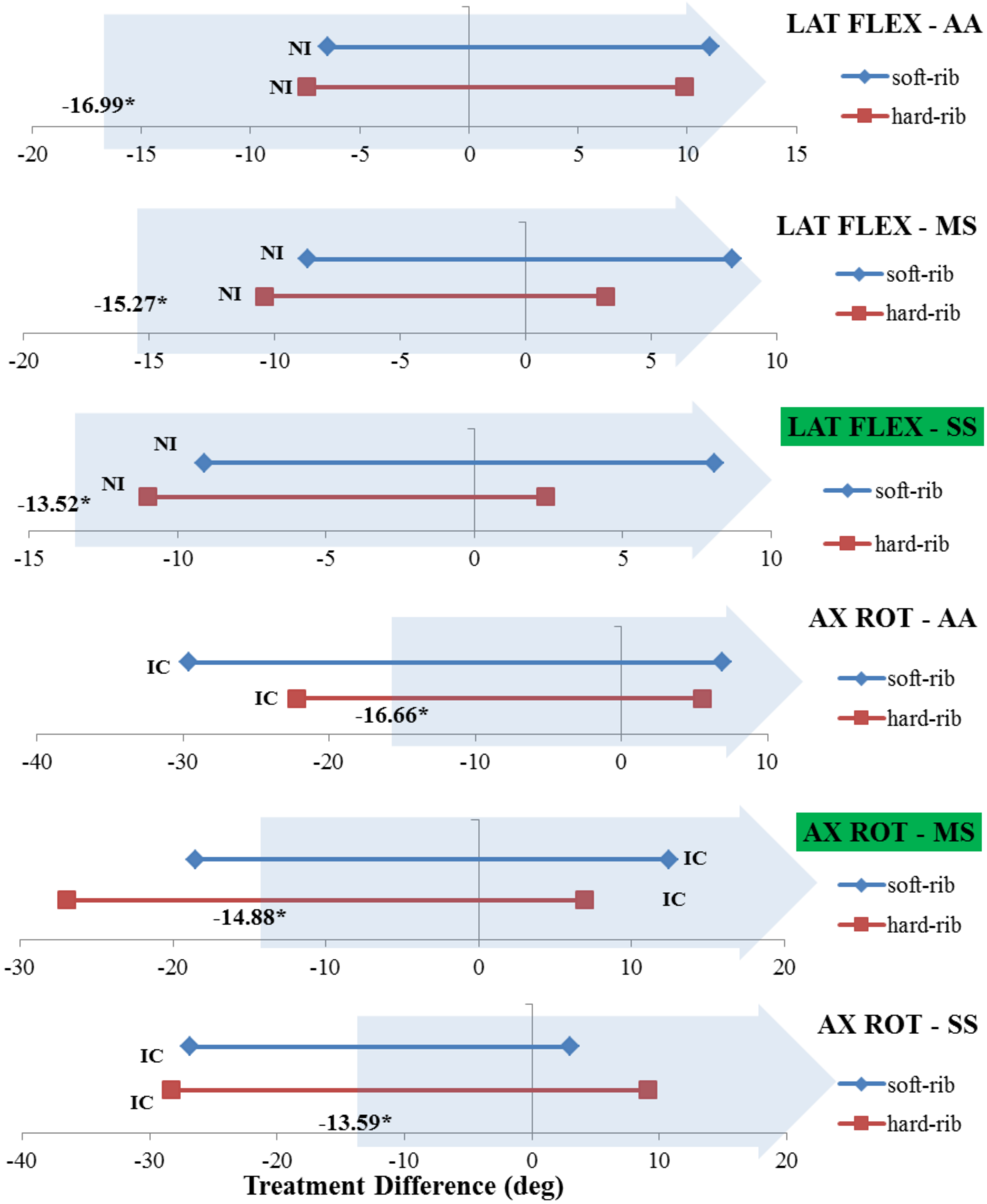

Figure 5.5 — Outcomes of non-inferiority testing for trunk ROM showed non-inferiority for lateral flexion (LAT FLEX) in all flexibility types for both rib protectors and inconclusive results for axial rotation (AX ROT) in all flexibility types for both rib protectors. Thin lines show 95% CI of treatment difference (protector – no-rib) for each rib protector. Large arrow represents the non-inferior range: tail is boundary at the non-inferiority margin (value in by bold text and * below X axis) and continues infinitely in the more 'favorable' difference direction. NI = non-inferior to NO-RIB and IC = inconclusive. The 'best' types for each condition, as determined by Factorial RM ANOVAs, are highlighted in dark green.

CHAPTER 6: Summary and Conclusions

Summary of Results

The soft-rib and hard-rib garments were non-inferior to the control for performance and lower trunk axial kinematics as predicted. All of the kinematic variables were correlated to ball speed, and time to maximum acceleration was also correlated to throw time. The perceptions of performance were inconclusive, before and after throwing, for the soft-rib and hard-rib as individuals had varying VAS scores across all conditions. For mobility, the soft-rib had inconclusive results before and after and the hard-rib showed inferiority to the control. Individuals had varying results for non-inferiority testing of throw performance and mobility variable outcomes. Most individual had inconclusive results for most variables. However, there were some non-inferior and inferior outcomes for both rib protectors and almost all variables.

ANOVA testing for flexibility demonstrated that there was no interaction between rib protection and flexibility task type for either lateral flexion or axial rotation. The flexibility task type main effect for lateral flexion indicated that the self-selected speed task produced the highest values for lower trunk range of motion (ROM) and was significantly greater than the maximal speed task. For axial rotation, the main effect for flexibility task type was not significant. However, the maximal speed and active-assisted protocols both had the highest values. For non-inferiority testing of the rib protectors using the flexibility type of the highest value (self-selected for lateral flexion and maximal speed for axial rotation), both rib protectors were non-inferior for lateral flexion

ROM and inconclusive for axial rotation ROM. However, both rib protectors' axial rotation ROM confidence intervals were centered in the non-inferiority range.

Conclusions

Neither rib protector garment (soft-rib, hard-rib) would cause most quarterbacks to perform any worse during an overhand throw, as they do not have any less trunk mobility or other reduced axial lower-trunk kinematics than they would while wearing just a compression shirt (control). However, there are some individuals who are affected differently than most other players so they should try multiple rib protectors until they find the one they are most comfortable and confident with. Rib protectors that have tangible textile materials perceived to constrict the trunk such as the hard plastic padding of the hard-rib, tend to cause individuals to perceive the garment to have an effect on mobility. However, these perceived properties of the protector do not necessarily translate to perceptions of effects on performance.

For lateral flexion, the best way to measure maximum lower trunk ROM is to have the participant bend at a self-selected speed. For axial rotation, it seems that an active-assisted or maximal speed protocol is best. However, maximal speed is the most applicable for mimicking active movements.

Implications

It is likely that quarterbacks can wear either variation of rib protector garment without hindrance of trunk mobility in either lateral flexion or axial rotation for throwing. The flexibility sub-study also suggests that movements such as cutting and lateral passing that involve lateral and/or axial trunk movement would also likely not be hindered by a rib protector garment[97]. These results can be used by coaches and athletic trainers to convince athletes to wear rib protectors if these protectors also are proven to be efficacious for preventing injury or attenuating rib/abdominal injury severity in American football quarterbacks in future epidemiological studies. As there is little influence of rib protector hardness/stiffness or rib protector on performance or axial trunk kinematics, except in few individual cases, it is important that a given individual quarterback be able to try different rib protectors and select the one that he feels the most comfortable and confident wearing.

The results of this study are useful in indicating which flexibility types tend to give the highest trunk ROM values when obtained via motion capture and showing that different flexibility types likely do not have to be used when comparing ROM while wearing sports equipment, particularly rib protectors, in the trunk area. However, we are making the assumption that the compression shirt had no influence on the flexibility types or outcomes. The self-selected flexibility type is most commonly used in trunk flexibility studies. Additionally, in clinical settings, measurements of trunk flexibility are usually conducted manually with inclinometers, goniometers, and/or tape measures either actively (both directions) or active-assisted (axial rotation) at a self-selected speed[98]. Maximal speed measurement is not practical for these manual measurements as individuals may lose some of the extra ROM that they achieved as they are trying to hold their position during measurement.

For lateral flexion, as the self-selected speed demonstrated the highest values for trunk ROM, it is likely best for clinicians and athletic trainers to continue to measure active flexibility at the participant's pace. However, for axial rotation, though the results were not significant, active-assisted at the participant's pace and maximal speed had the highest values for trunk ROM, indicating that the maximum ROM likely cannot be reached with the muscles alone and requires outside forces such as high momentum (maximal speed) or an applied torque (active-assisted) to get there. Clinicians should continue to use the self-selected pace flexibility protocols for lateral flexion but may want to consider mostly using an active-assisted protocol when measuring axial rotation trunk ROM to ensure that they get to the maximum end ROM. Specifically, when measuring changes in axial trunk ROM with motion capture while wearing rib protectors, maximal speed measurements seem to be the more applicable of the two flexibility types, as they mimic game movements, so those should be used.

Limitations

The biggest limitation within both studies was insufficient sample size. The initial target sample of 25 participants necessary to achieve sufficient power for both sub-studies could not be achieved; thus, twelve participants in the throwing study and eleven in the flexibility study were analyzed. Three eligible participants who were recruited initially sustained injuries before data collection that then made them ineligible. Still, non-inferiority testing for seven of the eleven variables in the throwing sub-study and all non-inferiority variables for flexibility had enough power. Only the initial RM ANOVA analysis didn't ($1\text{-}\beta = .4 - .78$).

Another limitation was that there are no reported values in the literature that indicate what the non-inferiority margin (NIM) should have been set to for non-inferiority tests of any of the variables for the throwing and flexibility. Behaviorally meaningful changes for lower trunk kinematics and throw performance have not been published. The NIM has a very significant influence on the outcome of non-inferiority testing. A conservative NIM could cause confidence intervals that would normally fall within the non-inferiority range to give inferior or inconclusive results. On the other hand, liberal NIMs can cause confidence intervals that should be outside of the non-inferiority range to give non-inferior or inconclusive results. Nevertheless, previous investigators have indicated that using the normal variability of the outcome measure is an acceptable alternative to using behaviorally significant changes[83].

A third limitation was that the compression shirt used in the control and hard-rib conditions was different than the one used in the soft-rib condition. As the rib protectors being tested were manufactured products on the market and the soft-rib padding was sewn into its compression shirt, the same shirts could not be used for all three conditions. The hard-rib padding was removable and the compression shirt was therefore able to be used as a control condition. There was no condition without any shirt at all, as the control was chosen to represent a sham condition. In addition, compression shirts or t-shirts are often worn under football padding to prevent sliding when perspiration occurs and to wick away moisture[23,24]. A posteriori informal stiffness testing showed that the hard-rib compression shirt provided similar compression to the soft-rib compression shirt (less than 8% difference) (Appendix F). This is because though the hard-rib shirt had a larger mean Young's modulus value compared to the soft-rib (**soft-rib** 25%mesh: 1.000×10^{-4} GPa, 75%solid: 2.401×10^{-4} GPa; **hard-rib** 60%mesh: 7.026×10^{-4} GPa, 40%solid: 4.878×10^{-4} GPa) (Appendix G), it was also thinner than the soft-rib (**soft-rib** mesh: .27mm, solid: .64 mm; **hard-rib** mesh: .46 mm, solid: .41 mm), making the overall stiffness roughly the same. Additionally, from qualitative questionnaires that the participants completed, only 2/11 participants indicated that the soft-rib was any tighter or more restrictive than the hard-rib or control compression shirts.

Finally, a fourth major limitation was that five of the participants had worn one of the rib protectors tested in the study and three more had worn some other type of rib protector. However, all outcomes were visually analyzed to determine if this was a confounding factor among individuals. Results, including perceptions, did not appear to be influenced by previous experience with a particular rib protector.

There were also several minor limitations within this study. First, as the target was not divided into quadrants, the highest accuracy did not necessarily mean the most precision. If five throws with the most precision rather than the most accuracy were able to be chosen, then lower trunk mobility values may have been less variable with throwing. Another minor limitation was that we were unable to control temperature of the rib protectors which may have slightly affected stiffness. However, all participants were measured in the same temperature-controlled indoor laboratory setting. Rib protectors conditions were tested in a counterbalanced order to minimize potential effects of any change in the participant's skin temperature during testing. Also, a minor limitation within both studies was the validity of the measures of lower-trunk axial rotation with motion capture. Surface markers likely contributed to the variability of the measurement, as has been noted by Hsu et al[52]. Marker dropout within a trial also contributes to error; however, the most accurate methods for filling gaps were used. In addition, skin movement artefact is an inherent limitation when using motion capture, particularly due to the geometry and mass of the marker clusters used in this study. However, Cover-roll® adhesive bandage was used to reinforce the marker cluster bases and a six-degrees of freedom pose estimation optimization method for computing the position and orientation of segments[85–88] was used to minimize the effects of these artefacts on the accuracy of the reconstructed marker locations.

Recommendations

As mentioned earlier, the efficacy of rib protectors in preventing rib injury needs to be determined. However, informal impact testing (Appendix E) showed that both garments can reduce the peak impact force and the max rate of application experienced with a compression shirt alone by almost half. Additionally, the National Operating Committee on Standards for Athletic Equipment (NOCSAE) has not set standards for rib protectors. Consequently, companies can sell protectors without having to provide any proof that they will attenuate forces from high impacts.

To be able to generalize the results found in this study to actual playing conditions, testing of these garments with football pads in the lab and in practice and game settings is needed. In addition, more research will need to be done on trunk ROM while wearing rib protector garments during other important, common movements performed during football, such as cutting, jumping, and/or lateral passing movements. There are other rib protector garments available, so testing of all protectors accessible to the public should be conducted.

Also, as many of the participants were wearing a rib protector for the first time or had not worn one in a long time, it is important to test the effects of all types of rib protectors on lower trunk kinematics and throw performance over a few weeks and/or months. Additionally, testing above and below the rib protection area as well as arm kinematics should be conducted to see if rib protector garments and other rib protectors alter other kinematics. This would determine if the mechanics and movements exhibit atypical alterations that could affect performance or cause abnormal tissue stresses. Concurrently, whether having previously worn a rib protector affects these outcomes should be determined as well.

Although not proven here, there may be a potential optimal range of flexibility that a quarterback may want to have in a game setting. The trunk needs to be able to rotate enough to effectively throw a ball quickly, accurately and, at times, as far as possible. In addition, other movements require some axial rotation and lateral flexion. However, some resistance may be helpful to prevent excessive trunk rotation when tackled. Therefore, this optimal range of flexibility should be determined.

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APPENDICES

A: Pre-Participation and Health Status Questionnaire

1 Rib Protector Garment 2016

Item 2:

Pre-Participation and Health Status Questionnaire

For researcher use only
Participant ID ______
Date __________
Researcher: ________________

When is your birthday? Month: _______ Day ________ Year _______

HEALTH AND MEDICAL CONDITIONS

If you now have or have had one of the conditions listed, put an X in the box provided. If you are unsure, put a question mark next to box.

- ☐ Heart problem
- ☐ Lung problem
- ☐ Trouble breathing or asthma
- ☐ Broken bones
- ☐ Sprains, or hurt an ankle, shoulder, hip, or knee
- ☐ Injury requiring major medical attention
- ☐ Spinal or Upper Extremity Abnormality
- ☐ Inner ear problem
- ☐ Pain lasting more than 2 weeks
- ☐ Balance problem
- ☐ Blurred or bad eyesight or other eye problem not corrected
- ☐ Surgery
- ☐ Acute injury to the spine or upper extremities (past 6 months)
- ☐ Other medical condition(s)

CURRENT HEALTH STATUS

Have you had during the past 2 weeks or have today, any of the following: (check all that apply)

- ☐ Discomfort or pain to any part of body
- ☐ Chest pain or tightness, tingling in arm
- ☐ Trouble breathing
- ☐ Injury
- ☐ Illness
- ☐ Any other health problems
- ☐ Feeling sick to your stomach
- ☐ Trouble with balance
- ☐ Trouble seeing
- ☐ Had any medical or dental procedures
- ☐ Feeling dizzy or light-headed
- ☐ Soreness

1. __Yes __No Are you taking or using any medications? If yes, list each, including those you can buy without a nonprescription:

____

2. Is there anything else that we should know concerning your health?

___ No ___ Yes ___ Maybe

B: Physical Activity History Questionnaire

1 Rib Protector Garment 2016

For researcher use only
Participant ID ______
Date __________
Researcher: _____________

Item 3:

Physical Activity History Questionnaire

1) Have you ever or do you currently play American football? **Circle one:** Yes No

   a. **If Yes**, on what level? **(Check all that apply)**
      - ☐ Professional
      - ☐ Semi-professional
      - ☐ Collegiate
      - ☐ Highschool
      - ☐ Club or Intramural
      - ☐ Adult League (Flag Football)
      - ☐ Youth League
      - ☐ Other ______________________

   b. **If Yes**, what position? **(Check all that apply)**
      - ☐ Quarterback
      - ☐ Wide Receiver
      - ☐ Running Back
      - ☐ Other Offensive Position, **Specify**: _______________
      - ☐ Defensive Position, **Specify**: _______________
      - ☐ Special Teams, **Specify**:_______________

2) How many hours per week do you participate in light activities?
   (Light activities = your heart beats slightly faster than normal; you can talk and sing. e.g. walking, stretching, light yard work)
      - ☐ 0 – 0.5 hrs
      - ☐ 0.5 – 1.0 hrs
      - ☐ 1.0 – 1.5 hrs
      - ☐ 1.5 – 2.0 hrs
      - ☐ 2.0 – 2.5 hrs
      - ☐ Other ______________________

3) How many hours per week do you participate in moderate activities?
   (Moderate activities = your heart beats faster than normal; you can talk but not sing. e.g. fast walking, aerobics class, strength training, swimming gently)
      - ☐ 0 – 0.5 hrs
      - ☐ 0.5 – 1.0 hrs
      - ☐ 1.0 – 1.5 hrs
      - ☐ 1.5 – 2.0 hrs
      - ☐ 2.0 -2.5 hrs
      - ☐ Other ______________________

(continued)

4) How many hours per week do you participate in vigorous activities?
(Vigorous activities = your heart rate increases a lot; you cannot talk or your talking is broken up by large breaths. e.g. jogging or running, intensive sports, stair machine)

- ☐ 0 – 0.5 hrs
- ☐ 0.5 – 1.0 hrs
- ☐ 1.0 – 1.5 hrs
- ☐ 1.5 – 2.0 hrs
- ☐ 2.0 -2.5 hrs
- ☐ Other ______________________________

C: VAS Scales

Item 3 **VISUAL ANALOG SCALE FOR PERFORMANCE**

For each rating, place a vertical mark on the line provided for the scale.

For researcher use only:
Participant ID: ____________
Researcher: ____________________
Date: ________________

------------------ --------------------- ----------------- -----------

Condition 1:

For researcher use only: RIB- ___ or CON (Circle one)

1. **Before completing tasks**

a. How mobile (able to move) do you feel?

Can't move |————————————————| Can move easier than ever before

b. How comfortable do you feel?

Most uncomfortable I have every felt |————————————————| Most comfortable I have ever felt

c. In a game setting, how protected would you feel wearing this under your football pads?

Most uncomfortable I have every felt |————————————————| Most comfortable I have ever felt

d. In a game setting, how well do you think you could complete a pass to a teammate while wearing this under your football pads?

Can't complete a pass |————————————————| Can complete a perfect pass anywhere on the field

2. After completing tasks

a. How mobile (able to move) do you feel?

Can't move	|——————————|	Can move easier than ever before

b. How comfortable do you feel?

Most uncomfortable I have every felt	|——————————|	Most comfortable I have ever felt

c. In a game setting, how protected would you feel wearing this under your football pads?

Most uncomfortable I have every felt	|——————————|	Most comfortable I have ever felt

d. In a game setting, how well do you think you could complete a pass to a teammate while wearing this under your football pads?

Can't complete a pass	|——————————|	Can complete a perfect pass anywhere on the field

Condition 2:

For researcher use only: RIB- ___ or CON (Circle one)

3. **Before completing tasks**

   a. Have you ever worn a rib protector before? Y or N (Circle one)
   ...this rib protector before? Y or N (Circle one)

   b. How mobile (able to move) do you feel?

Can't move |————————————————| Can move easier than ever before

   c. How comfortable do you feel?

Most uncomfortable I have every felt |————————————————| Most comfortable I have ever felt

   d. In a game setting, how protected would you feel wearing this under your football pads?

Most uncomfortable I have every felt |————————————————| Most comfortable I have ever felt

   e. In a game setting, how well do you think you could complete a pass to a teammate while wearing this under your football pads?

Can't complete a pass |————————————————| Can complete a perfect pass anywhere on the field

4. After completing tasks

a. How mobile (able to move) do you feel?

Can't move |————————————| Can move easier than ever before

b. How comfortable do you feel?

Most uncomfortable I have every felt |————————————| Most comfortable I have ever felt

c. In a game setting, how protected would you feel wearing this under your football pads?

Most uncomfortable I have every felt |————————————| Most comfortable I have ever felt

d. In a game setting, how well do you think you could complete a pass to a teammate while wearing this under your football pads?

Can't complete a pass |————————————| Can complete a perfect pass anywhere on the field

Condition 3:

For researcher use only: RIB- ___ or CON (Circle one)

5. Before completing tasks

a. Have you ever worn a rib protector before? Y or N (Circle one)

...this rib protector before? Y or N (Circle one)

b. How mobile (able to move) do you feel?

Can't move — Can move easier than ever before

c. How comfortable do you feel?

Most uncomfortable I have every felt — Most comfortable I have ever felt

d. In a game setting, how protected would you feel wearing this under your football pads?

Most uncomfortable I have every felt — Most comfortable I have ever felt

e. In a game setting, how well do you think you could complete a pass to a teammate while wearing this under your football pads?

Can't complete a pass — Can complete a perfect pass anywhere on the field

6. After completing tasks

a. How mobile (able to move) do you feel?

Can't move |————————————————| Can move easier than ever before

b. How comfortable do you feel?

Most uncomfortable I have every felt |————————————————| Most comfortable I have ever felt

c. In a game setting, how protected would you feel wearing this under your football pads?

Most uncomfortable I have every felt |————————————————| Most comfortable I have ever felt

d. In a game setting, how well do you think you could complete a pass to a teammate while wearing this under your football pads?

Can't complete a pass |————————————————| Can complete a perfect pass anywhere on the field

Condition 4:

For researcher use only: RIB-___ or CON (Circle one)

7. Before completing tasks

a. Have you ever worn a rib protector before? Y or N (Circle one)

...this rib protector before? Y or N (Circle one)

b. How mobile (able to move) do you feel?

Can't move |———————————| Can move easier than ever before

c. How comfortable do you feel?

Most uncomfortable I have every felt |———————————| Most comfortable I have ever felt

d. In a game setting, how protected would you feel wearing this under your football pads?

Most uncomfortable I have every felt |———————————| Most comfortable I have ever felt

e. In a game setting, how well do you think you could complete a pass to a teammate while wearing this under your football pads?

Can't complete a pass |———————————| Can complete a perfect pass anywhere on the field

8. After completing tasks

a. How mobile (able to move) do you feel?

Can't move ├──────────────┤ Can move easier than ever before

b. How comfortable do you feel?

Most uncomfortable I have every felt ├──────────────┤ Most comfortable I have ever felt

c. In a game setting, how protected would you feel wearing this under your football pads?

Most uncomfortable I have every felt ├──────────────┤ Most comfortable I have ever felt

d. In a game setting, how well do you think you could complete a pass to a teammate while wearing this under your football pads?

Can't complete a pass ├──────────────┤ Can complete a perfect pass anywhere on the field

D: Rib Protection Ranking Questionnaire

Item 4 **RIB PROTECTION RANKING**

For researcher use only:
Participant ID: ___________
Researcher: ________________
Date: ______________

Please rank each of the rib protector conditions compared to each other in each of the following categories. Multiple conditions can have the same ranking. (1= best; 4= worst)

---

1) Mobility:

	best			worst
CON	1	2	3	4
RIB-A	1	2	3	4
RIB-B	1	2	3	4

Comments/Feedback:

____

____

____

____

2) Comfort:

	best			worst
CON	1	2	3	4
RIB-A	1	2	3	4
RIB-B	1	2	3	4

Comments/Feedback:

____

____

____

____

3) Protection:

	best			worst
CON	1	2	3	4
RIB-A	1	2	3	4
RIB-B	1	2	3	4

Comments/Feedback:

____

____

____

____

4) Your ability to perform while wearing it:

	best			worst
CON	1	2	3	4
RIB-A	1	2	3	4
RIB-B	1	2	3	4

Comments/Feedback:

____

____

____

____

5) Overall:

	best			worst
CON	1	2	3	4
RIB-A	1	2	3	4
RIB-B	1	2	3	4

Comments/Feedback:

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Had you ever worn a rib protector before today? Y N **(Circle one)**

If yes-

If ones in this study, which one(s)? RIB-A RIB-B **How long?** _______________

If others, what brand(s)?________________________ **How long?** _______________

E: Impact Testing

Instrumentation

Vertical ground reaction force was obtained using a force plate (Bertec^{TM} 4060-NC) sampling at 960 Hz.

Protocol

Each rib protector was cut along the length of the shirt and the rib area was laid flat onto the center of the force plate with the inside facing down. A 2.2 kg weight was dropped from 38 cm above the force plate onto each of the three rib protector conditions' rib areas (control, soft-rib, hard-rib). This was completed a total of five times.

Data Reduction

The first impact was analyzed for each trial. The peak impact force and the maximum rate of application were determined for each trial within a condition. The values across the five trials were averaged for each variable in each condition.

Results

Table A.1 — Impact Testing Results for the Rib Protector Conditions

Rib Condition	**Peak Impact Force (N)**		**Max Rate of Application (N/s)**	
	Average	*SD*	*Average*	*SD*
soft-rib	1351.63	236.75	492,764.70	292,027.34
hard-rib	1401.62	320.63	644,709.90	59,426.70
Control	2357.67	355.28	1,458,047.23	226,019.99

Figure A.1 — Impact Testing Experimental Setup

F: Stiffness Testing (Shirt Level)

Protocol

Each rib protector condition was hung horizontally against a wall on hooks above and below the rib protection area with the rib protector padding flat against the wall on both sides of the garment. A tape measure was taped against the wall behind the rib protector garment. The original width of the garment was measured using the tape measure. A 2 kg weight was then placed into the garment at the horizontal center of the rib protection area so that the compression shirt was stretched. The final width of the garment was then measured. This was repeated five times.

Data Reduction

The stiffness of the garment was determined for each garment as the load (2 kg) divided by the elongation of the garment (change in length). The stiffness's across the five trials were averaged for each condition.

Results

Table A.2 — Garment Level Stiffness Testing Results for the Rib Protector Conditions

Rib Condition	**Stiffness (N/m)**	
	Average	*SD*
soft-rib	227.57	7.33
hard-rib	246.35	15.48
Control	184.35	5.66

G: Stiffness Testing (Fabric Level)

Protocol

Approximately 16 cm by 4.5 cm fabric samples were horizontally cut out from the mesh (back) and the solid (front) compression areas of the hard-rib and soft-rib compression shirts. Each fabric sample was then taped along the top and bottom to expose a 12 cm by 4.5 cm test area (Figure A.2a). For each fabric sample, the sample was clamped along the top piece of tape and a separate clamp containing a given mass to be tested (0.2, 0.4, 0.6 kg) was clamped to the bottom along the other piece of tape (Figure A.2b). The stretched length was then measured and recorded. This was repeated a total of three times for each sample, for each mass.

Data Reduction

The lengths for each of the three trials within a given sample and weight were averaged and used to calculate the strain (ε) = (final length – initial length) / initial length. The stress (σ) = (mass x 9.8 m/s^2)/(thickness of the fabric sample x width of the fabric sample) was calculated for each of the masses and samples. The strain vs stress for each of the masses was then plotted for each sample to determine a line of best fit and the slope was taken to determine Young's Modulus (Table A.3).

Results

Table A.3 — Fabric Level Stiffness Testing Results for the Compression Shirts

Rib Condition	Young's Modulus (GPa)
soft-rib mesh	1.000×10^{-4}
soft-rib solid	2.401×10^{-4}
hard-rib mesh	7.026×10^{-4}
hard-rib solid	4.878×10^{-4}

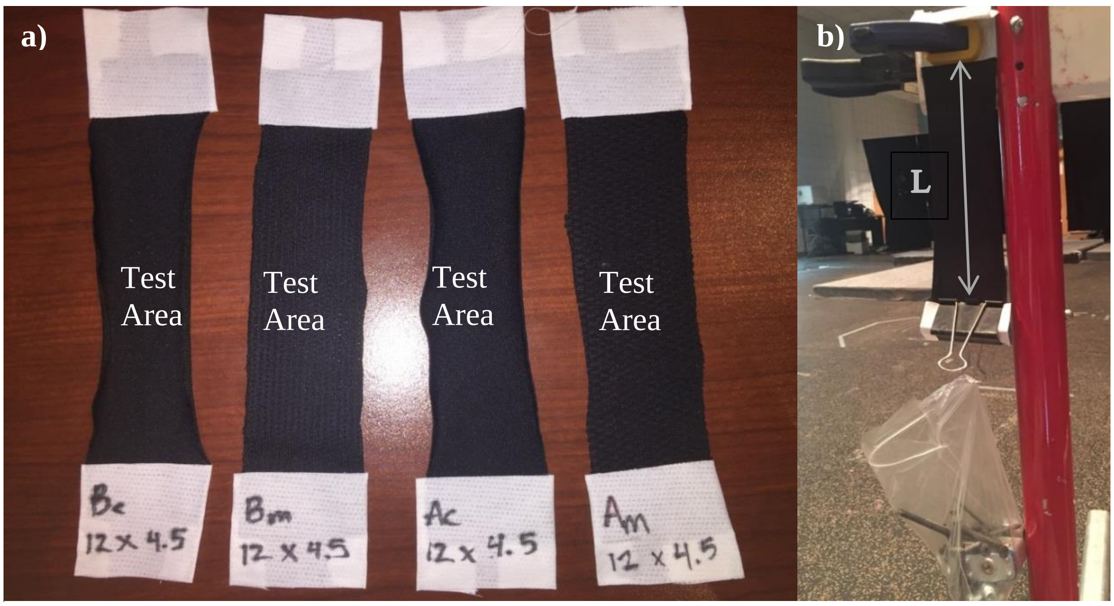

Figure A.2 — Samples and Experimental Setup for Fabric Level Stiffness Testing. **(a)** The fabric samples being used for testing were: soft-rib mesh (A_m), soft-rib solid (A_c), hard-rib mesh (B_m), and hard-rib solid (B_c). The fabric test area was 12 cm long and 4.5 cm wide. **(b)** The test set up involved the sample clamped at the top and the weight clamped to the bottom. The resulting length (L) was then measured.