Determining the Effects of Force Intensity, Postural and Force Direction Constraints on Off-Axis Force Production during Static Unilateral Pushing and Pulling Manual Exertions

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Proactive ergonomics is generally considered to be a more efficient and cost effective way of designing working environments than reactive ergonomics. It often requires preemptively selecting working postures and forces to reduce potential injury risk. One major issue with proactive ergonomic design is correctly identifying the true manual forces that will be required of a worker to complete defined tasks. Typically, these forces are represented as in direct opposition to the forces required by a particular task. However, this is likely an oversimplification as forces often act in different directions than the task-required direction to increase required force level, enhance balance and reduce joint moments, depending on specific experimental conditions. This study aims to quantify these off-axis forces as they change with different required on-axis force intensities.

This thesis evaluated the effects of force intensity on the presence of off-axis forces across four conditions, which included free and constrained postures, and with and without off-axis force. Eighteen female subjects performed static, unilateral, manual pushing and pulling exertions while seated and were limited to force contributions from the right upper extremity. Hand forces and location of bony landmarks were collected from each subject and force intensity consisted of both maximal and submaximal levels (5% to 50% of the maximum producible on-axis force in increments of 5%). All principle direction forces were scaled to the on-axis force level and anatomically relevant joint moments scaled to the maximum capacity joint moment.

The main objective of this study was to analyze off-axis force production as force intensity was increased under various constraint conditions. The highest maximum on-axis force was in the fully free condition (off-axis force allowed and posture unconstrained) and as conditions became more constrained for both pushing and pulling exertions, maximum on-axis force production decreased (p=<0.0001). For submaximal exertions in the free posture, participants used off-axis forces to target the shoulder flexion-extension moment by pushing increasingly upwards (p=0.0122) and to the left by 5.6% on-axis (p=0.0025), and by pulling 12.6% on-axis downward (p=<0.0001) and 4.7% on-axis rightward (p=0.0024) compared to when off-axis force was not allowed. When comparing the free to the constrained posture while allowing off-axis force, participants pushed downwards instead of upwards by a difference of 12.9% on-axis (p=0.0002) and pulled less downward (becoming slightly upward) by an increasing difference (p=0.0002) and from decreasing to increasing rightward (p=0.0006). These changes in off-axis force showed a unifying strategy of using less shoulder flexion-extension strength by targeting wrist and elbow moments for pushing and pulling exertions. When in the constrained posture allowing and not allowing off-axis force resulted in more internal elbow flexion (p=0.0003) moment during pushing, and less internal shoulder flexion (p=0.0092), more internal shoulder adduction (p=0.0252), more to less internal elbow supination (p=0.0415), and increasingly less internal wrist flexion (p=0.0296) moments during pulling, which verified previously observed strategies. Finally, for both maximal and submaximal exertions, pulling was more sensitive to changes in off-axis forces compared to pushing which was more sensitive to postural flexibility. In conclusion, the underlying principles as to how and why off-axis forces change provides valuable knowledge to ergonomists so that they can more accurately predict force production in workplace design, ultimately reducing the potential for injury.

Acknowledgements

“Started from the bottom now we’re here” (Drake, 2013)

I would like to thank my study participants for providing the raw data; my colleagues Tyler, Alan, and especially Meagan Warnica for assisting in collecting the data; Erin Harvey for making statistical sense of the data; and my supervisor, Dr. Clark Dickerson, and committee members, Dr. Richard Wells and Dr. Stacey Acker, for throwing the data back at me and demanding conclusions.

Last but not least, I would like to thank my sisters and my extended family for their unconditional love.

Dedication

I dedicate this thesis to my parents for loving and supporting me through this endeavor.

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I. Introduction

1.1 Proactive Ergonomic Design

In practice, workplace interventions often follow the occurrence of an injury. This is referred to as reactive ergonomic design and is effective at preventing future injury but at the cost worker's health. Conversely, proactive ergonomic design aims to identify and eliminate potential workplace risks before they occur by "designing problems out of the product and process before reaching the operation phase" (Joseph, 2003). This approach to workplace design is more effective and cost-efficient (Joseph, 2003) as well as sparing to workers' health. For example, once proactive ergonomics was implemented in the automotive sector, launching a new engine line resulted in over six months of plant operation without a lost time upper extremity musculoskeletal disorder, and launching a new vehicle assembly line required less modification of workstations and an overall reduction in worker injury (Joseph, 2003). Thus, ergonomists strive to implement proactive designs into the workplace.

In order to implement proactive design, anticipated working conditions need to be determined and quantified *a priori*. This includes predicting how workers will position themselves and what forces will be required to complete the intended work tasks. From this information, joint angles, contact forces and moments can be calculated and interpreted to see if they indicate reduced injury risk. Accurately predicting both body posture and external hand forces is important to ensure the level of estimated injury risk is of good fidelity. Misestimating these values may result in misestimates of injury risk, potentially defeating the purpose and eliminating the benefits of proactive design.

1.2 Determining Working Forces

Despite well-known limitations in methods used to predict working postures, this thesis focused on the difficulties with estimating external forces associated with occupational task performance. In particular, the external forces applied at the hand and their effects on upper extremity kinematics were examined.

A common technique for hand force estimations is to apply forces to the worker that are opposite in direction and equal in magnitude to the known forces required to complete the specific work task. This results in the applied hand force acting parallel to the force exerted on work interfaces, such as tools or parts. For example, cart pushing is often represented by a horizontal vector at the hand with a magnitude proportional to the mass of the cart (Chaffin, Andersson, & Martin, 2006). In some cases, this estimation can be more accurate as ergonomists can "use product specification data to estimate the magnitude of required force (for example, the nominal insertion force for a part) and infer hand force direction from part geometry" (Hoffman, Reed, & Chaffin, 2011).

The problem with these methods is that when applied forces are physically measured they exist for multiple axes. In fact, it has been observed that naïve subjects typically produce force along multiple directional axes to maximize force production (Grieve & Pheasant, 1981). To fully account for the variations observed in joint loading, the force magnitude and force direction with respect to posture needs to be properly characterized (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000). Unfortunately, current methods employed to predict hand force typically do not account for directional deviation of the force from the nominal direction. As such, the resulting predictions of joint moments and forces may be misestimated, leading to inaccurate predictions of injury risk for proposed workplace designs.

1.3 Justification for Current Methods of Force Prediction

Acknowledgement of these errors motivates changing practice, however, difficulties remain. The principal issue is that the actual hand force direction is prospectively unknown for most manual work scenarios. This stems from a fundamental lack of understanding of the influence of different working conditions on the nature of applied external manual loads. Examination of how the direction of hand force changes with the required position of exertion (height and width from body), magnitude of exertion, exertion type (pushing, pulling, lifting, lowering), gross body posture of the worker (seated, standing), and contact surface characteristics (handle type, friction requirements) have not been extensively quantified in literature. Further, understanding the underlying mechanisms that determine the direction and magnitude of the applied external hand force are incompletely characterized. Theories including minimizing joint moments to accommodate for strength (Hoffman, Reed, & Chaffin, 2008) (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000) (Seo & Armstrong, 2009), reducing fatigue of certain muscles as a protection method (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000) and compensating for whole-body balance (Hoffman, Reed, & Chaffin, 2011) (Wilkinson, Pinder, & Grieve, 1995), have been suggested as potential mechanisms but not specifically examined or quantified. These limitations make it difficult to apply experimental observations to realistically predict hand force and as a result proactive ergonomic designs remain inaccurate.

1.4 Defining On- and Off-Axis Forces, Moments, and Push and Pull Exertions

The applied external hand force is often referred to as the resultant or actual force. For the purposes of this thesis, this force was broken into three components (Figure 1.1):

1. On-axis force: the component of the force acting along the intended directional axis

2. Off-axis force(s): the component(s) of the force acting along axes perpendicular to the intended axis and;

3. Moment(s): the moment(s) acting around each of the three principal axis

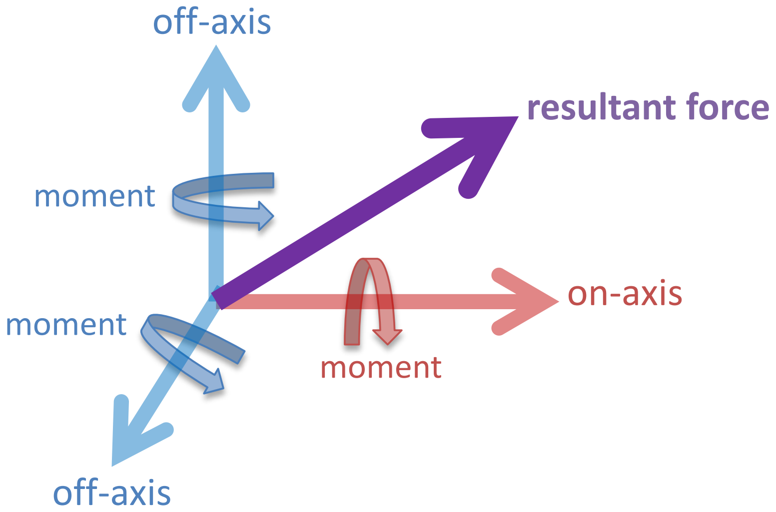

Figure 1.1 On- and off-axis forces, and moments for a horizontal push to the right

In this thesis, push and pull exertions were defined as pushing forward and pulling. This implies that on-axis force during pushing was in the forward (anterior) direction and on-axis pulling was in the backward (posterior) direction. Off-axis forces occurred in the superior-inferior (up-down) and medial-lateral (left-right) directions for these exertion types.

1.5 Purpose

The following thesis had two underlying purposes. The first purpose was to quantify off-axis forces during pushing and pulling at different fractions of capacity. This purpose is relevant to ergonomic design, as the influence of normalized exertion level on the production of off-axis forces was characterized. The second purpose was to describe the underlying biomechanical motivation for producing off-axis forces as they pertain to individual and overall upper limb joint strengths. This purpose is biomechanically significant and added to current fundamental understanding of human upper extremity manual force production.

1.6 Hypotheses

Four hypotheses were used to achieve the aforementioned purposes. The first three hypotheses pertained to the first purpose:

1. Maximum producible force in the on-axis direction would decrease as off-axis force was not allowed and as posture was constrained.

2. As required submaximal on-axis force level was increased, the presence of off-axis force would also increase for pushing and pulling exertions.

3. If posture was constrained the production of off-axis force would increase as the normalized exertion level increased, compared to if posture was not constrained. This would be in response to reduced postural flexibility, as participants would not be allowed use postural adjustments to achieve the required force exertions.

The final hypothesis pertained to the second purpose:

4. As normalized exertion level was increased in the constrained posture, normalized joint moments would be reduced when off-axis force was allowed compared to when it was not allowed. This change would correspond to manual force producing strategies that reduced the overall impact of the exertion on specific joints and/or employed a change in the use of specific muscle groups.

II. Literature Review

2.1 Previous Studies which Evaluate Off-Axis Force Production

Few studies have targeted the evaluation of off-axis force production during manual exertions. However, many studies have found the production of these forces inadvertently while examining other phenomena. The following sections summarize the major findings of studies that have reported the production of off-axis forces during push and pull exertions at the hand.

2.1.1 Off-Axis Forces Increase On-Axis Force Production

Off-axis forces produced at the hand correspond with an increase in on-axis force. On-axis maximum push and pull force was 38% higher for a stable handle (off-axis forces permitted) versus a non-stable handle (no off-axis force allowed) (Seo & Armstrong, 2009). Similarly, it was found that during one-handed seated exertions at a fixed arm position (arm adducted and flexed 20 degrees, 110 degree elbow included angle, and 90 degree pronation of the hand), maximum producible force in the on-axis direction decreased by 20% when the handle was unstable in the horizontal direction and 26% when it was unstable in the vertical direction compared to a fully stable handle condition (Bober, Kornecki, Lehr, & Zawadzki, 1982). One purpose of the study is to determine how off-axis force production changes with changing force intensity as such if off-axis forces are linked with higher on-axis force production they may increase with increasing force intensity.

2.1.2 Typical Directions for Off-Axis Forces during Pushing and Pulling

Consistent directions of off-axis force generated during pushing and pulling have been reported. The first study evaluated seated, one-handed, static push and pull exertions on both a stable (allows for off-axis force production) and non-stable (no off-axis force production) horizontal handle. Increases in on-axis force production with the stable handle compared to the non-stable handle were associated with a vertical, off-axis component of the hand force (Seo & Armstrong, 2009). This vertical force component was significantly different ($p < 0.025$) from zero and was downward during pushing and upward during pulling (Seo & Armstrong, 2009). The lateral off-axis force was not identified as significant for the exertions (Seo & Armstrong, 2009). This study was limited as only one handle location was evaluated. Similarly, during standing, two-handed, full-body push and pull exertions with the handle located overhead (total height plus ten centimeters), subjects pushed in an upward direction (downward reaction force) during pushing and a downward direction (upward reaction force) during pulling (Hoffman, Reed, & Chaffin, 2011). On the contrary, for lower handle heights these relationships were less pronounced during pushing and the opposite for pulling as a downward reaction force was present (Hoffman, Reed, & Chaffin, 2011). Again, lateral components were minimal and for the majority of exertions accounted for less than 15% of the on-axis force (Hoffman, Reed, & Chaffin, 2011). Two-handed dynamic pushing and pulling of a four-wheeled trolley with horizontal handles) on two floor surfaces with different coefficients of friction has also been studied. Similar to the aforementioned studies, at the hand a downward vertical force component was noted during pushing and an upward vertical force component during pulling (Boocock, Haslam, Lemon, & Thorpe, 2006). Lateral force components were also produced but these were attributed to reducing the potential for rotational forces acting on the trolley (Boocock, Haslam, Lemon, & Thorpe, 2006).

Even though these studies attributed the vertical components of hand force to different causes, to compensate for reduced wrist flexion/extension strength (Seo & Armstrong, 2009) and to compensate for reduced floor friction (Hoffman, Reed, & Chaffin, 2011) (Boocock, Haslam, Lemon, & Thorpe, 2006), all studies found the changes in off-axis forces to be the same for pushing and pulling. One purpose of the current work is to diagnose the root cause of these directional forces.

2.1.3 Effects of Handle Location and Force Level

Many studies conducted on push and pull exertions have focused on the interplay between changing handle locations and force levels on the direction and/or magnitude (in the on-axis direction) of manual exertions. These two factors relate to the direction of applied force and subsequently the presence and magnitude of off-axis forces. During dynamic, two-handed exertions, as the handle height increased from 60-80% shoulder height in pushing and 50-70% shoulder height in pulling and force level increased from 15-45% body weight, pushing direction changed from downward to near-horizontal and pulling changed from upward to near horizontal (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000). This effect was more pronounced for pushes than pulls (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000). Handle height also had a smaller effect than force level on net shoulder torque in the sagittal plane (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000) indicating that force level may play a bigger role in the production of off-axis forces. Similarly, the ratio of horizontal to resultant force was calculated during maximal, two-handed, standing pushing exertions at different handle heights (30% to 80% vertical reach height for males and 60% to 100% shoulder height for females) and back foot positions relative to the vertical plane of the force handle (30% to 70% vertical reach height for males and 50% to 90% shoulder height for females) (Ayoub & McDaniel, 1974). The maximum ratio (indicating the least presence of off-axis forces) was at 50% vertical reach height (males) or 70% to 80% shoulder height (females) and at a foot distance of 70% vertical reach height (males) (Ayoub & McDaniel, 1974). Females were less sensitive to changes in foot position than males thus only the male's foot position was reported (Ayoub & McDaniel, 1974). The ratio on either side of the maximum decreased for both males and females indicating increases in off-axis force production as the handle height was increased or decreased from the aforementioned height (Ayoub & McDaniel, 1974). In a different study, during two-handed pushing exertions significantly larger maximum horizontal force was observed at waist height conditions versus shoulder height conditions (Granata & Bennett, 2005). Further, as handle height increased from waist to shoulder and force level increased from 15% body weight to maximum, the direction of applied force changed from horizontal or slightly downward to upward (Granata & Bennett, 2005). Similarly, during standing two-handed, static push and pull exertions at three heights (overhead, elbow-height and thigh-height) and four force levels (25, 50, 75 and 100% of maximum), the largest off-axis forces were present in the vertical direction accounting for 32% during pushing and 52% during pulling of the on-axis force; whereas lateral off-axis forces accounted for less than 15% of the on-axis force in majority of cases (Hoffman, Reed, & Chaffin, A study of the difference between nominal and actual hand forces in two-handed sagittal plane whole-body exertions, 2011). At elbow-height and overhead, the vertical off-axis force increased with increasing required force level (from 25-100%) (Hoffman, Reed, & Chaffin, 2011). On the contrary at thigh-height the vertical off-axis force, which was directed downwards became less negative with increasing required force level (Hoffman, Reed, & Chaffin, A study of the difference between nominal and actual hand forces in two-handed sagittal plane whole-body exertions, 2011). For pulling, the vertical off-axis force was directed downward overhead and became more upward as handle height decreased from elbow-height to thigh-height (Hoffman, Reed, & Chaffin, A study of the difference between nominal and actual hand forces in two-handed sagittal plane whole-body exertions, 2011).

2.2 Theories of Why Off-Axis Forces are Produced

Within studies that have either evaluated off-axis forces or have noted the presence of off-axis forces, causation theories are typically presented, though conclusive evidence is elusive. The following sections summarize major theories of why off-axis forces are produced at the hand during pushing and pulling tasks.

2.2.1 Reduce Specific Joint Moments

One common theory as to why off-axis forces are created is to exert force such that there is a reduction and/or targeting of certain joint moments. It is thought that subjects adopt methods of exertion and/or postures, which increases the prevalence of off-axis forces, and this is associated with increases and/or decreases in specific joint moments. The following studies have shown evidence of this occurring at different joints during different types of pushes and pulls.

During two-handed isometric pushes, participants modified their posture to align the axis of the spine with the external force vector resulting in a reduced external trunk moment (Granata & Bennett, 2005). This was completed by adjusting the trunk flexion angle by changing the elbow flexion angle and was shown to increase with increasing level of exertion (Granata & Bennett, 2005). Further analysis using a biomechanical model indicated that as the applied angle of external hand force became more horizontal, the external stability at the L5/S1 joint was reduced (Granata & Bennett, 2005). This indicates a protective mechanism may exist to ensure hand forces are produced at such an angle to increase joint stability. Similarly, when producing one-handed push and pull exertions at elbow-height and at levels ranging from 25% to 100% of maximum effort, a great variation in torso rotation angle (from -40 to 105 degrees) was observed and attributed to the reduction in the moment arm between the point of force application and the L5/S1 joint which reduces the low-back rotational moment (Hoffman, Reed, & Chaffin, 2008). This torso rotation angle was found to significantly increase with increasing hand force during pull exertions (Hoffman, Reed, & Chaffin, 2008). In a different study, a strategy to minimize energetic and mechanical loads by minimizing net joint moments in the shoulder was observed during two-handed push and pull exertions while walking on a treadmill (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000). This was achieved by adjusting posture to direct the line of action of the force slightly below the shoulder rotation axis (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000). Similarly but at the wrist, subjects applied a downward off-axis force during one-handed pushing and an upward off-axis force during one-handed pulling on a horizontal handle while seated (Seo & Armstrong, 2009). These upward and downward off-axis forces generated a moment about the wrist flexion-extension axis which opposed the moment created by the reaction force from the applied exertion and reduced the total external moment at the wrist (Seo & Armstrong, 2009). This provides evidence that off-axis forces on a handle are produced to reduce external joint moments at the wrist (Seo & Armstrong, 2009) but unlike the aforementioned studies is limited to the assumed subject posture (subjects were seated, handle at elbow height, with an extended elbow posture). The authors indicate that subject posture was a limit to the study design and that predicted hand force production, and associated external joint moments, would change with different arm postures (Seo & Armstrong, 2009).

2.2.2 Compensation for Changing Floor Friction

A common difference in pushing and pulling studies is whether subjects are standing for the exertions or sitting. This is important is because one of the primary limiting factors to hand force production during pushing and pulling is balance relating to the shoe-floor friction interphase (Chaffin, Andersson, & Martin, 2006) (Hoffman, Reed, & Chaffin, 2011) (Fischer S. L., 2011). Thus, another major theory as to why off-axis forces are produced during standing push and pull exertions is to increase the downward vertical component of the reaction force at the hand to reduce slipping and increase balance. The following studies have shown this result.

During two-handed dynamic trolley pushing and pulling, an average increase of 41.3 N downward for pushing and an average decrease of 48.1 N upward for pulling, in the vertical component of the hand force was observed as floor friction was reduced (Boocock, Haslam, Lemon, & Thorpe, 2006). The overall net effect of these observed changes in the vertical component of the hand force (increased downward vertical components) was to reduce the required coefficient of friction to prevent slipping (Boocock, Haslam, Lemon, & Thorpe, 2006). Even though not statistically significant, during two-handed dynamic cart pushing, the ratio of vertical to horizontal force during both the initial and sustained phases of pushing was found to increase when pushing on high friction to low friction floors (Ciriello, McGorry, & Martin, 2001). Increasing this ratio would again help reduce the risk of slipping. Similarly, during two-handed isometric pushes, as handle height and required force level increased, subjects tended to push from a downward direction to an upward direction which increased the downward component of the reaction force at the hand subsequently increasing the normal ground reaction force and reducing slip (Granata & Bennett, 2005). This result was also observed during two-handed, full-body, push exertions at elbow- and thigh-heights, as subjects tended to push more upward on the handle as required force level was increased (Hoffman, Reed, & Chaffin, 2011). This transition in applied force direction occurred sooner (at approximately 50% capability) for elbow-height exertions compared to thigh-height exertions (Hoffman, Reed, & Chaffin, 2011) indicating that higher handle heights are more prone to balance limitations. Again these changes in resultant force direction were attributed to increasing the vertical ground reaction force and resulting in reduced slip potential (Hoffman, Reed, & Chaffin, A study of the difference between nominal and actual hand forces in two-handed sagittal plane whole-body exertions, 2011).

2.2.3 Compensation for Limited Wrist Strength

When evaluating manual force production, a few studies have come to the conclusion that wrist posture (defined by radial and ulnar, and flexion and extension angle) and strength are two of the main determinates of producible force at the hand and may be the cause of off-axis forces.

Wrist posture during pushing and pulling exertions at the hand has an effect on the producible force and may limit the strength of the upper extremity. A relationship between wrist flexion-extension posture and the amount of force present along the medial-lateral axis of the wrist existed during exertions such that high forces were applied along this axis in an extended wrist posture and low forces in flexed wrist postures (Okunribido & Haslegrave, 2008). Similarly, wrist posture was a significant indicator of both wrist flexion and radial deviation strength such that the wrist flexion strength was 10.5% stronger with the wrist extended at 45 degrees compared to a neutral posture and the wrist radial deviation strength was 20.5% stronger for 30 degrees ulnar deviation compared to a neutral posture (Al-Eisawi, Kerk, & Congleton, 1998). Elbow angle did not influence the tested strengths (Al-Eisawi, Kerk, & Congleton, 1998), supporting that wrist posture was the limiting factor to producible hand force.

Wrist strength is also limiting to the producible hand force during pushing and pulling exertions. When subjects performed static strength tests, seated, at specific elbow and wrist angles, “wrist strength limited the exertion of maximal moments about the elbow only when the exertion about the wrist was in the flexion direction and the wrist was extended” at an angle of 45 degrees (Al-Eisawi, Kerk, & Congleton, 1998). This indicates that for extended wrist postures, the flexion-extension strength of the wrist may be the “weakest link” in the upper extremity. As such, off-axis forces may be created to reduce the flexion-extension moment at the wrist thus compensating for lack of strength about this axis. During this study it was also noted that subjects that demonstrated weaker wrist strength showed more strength limitations than subjects with stronger wrist strength (Al-Eisawi, Kerk, & Congleton, 1998), which strengthens the argument that wrist strength is determining moment trade-offs at the elbow and limiting hand force production. Similarly, when pushing and pulling, seated, with one hand on both a stable (allows for the production of off-axis force) and a non-stable handle (only on-axis force), prediction of the on-axis force based on wrist flexion and extension strength and the measured vertical component of force was correct within one standard error (Seo & Armstrong, 2009). This indicates that wrist strength is a strong predictor of producible hand force. In a different study, during one-handed seated exertions at three force levels (40%, 60% and 100% on-axis force) and a fixed arm position (arm adducted and flexed 20 degrees, 110 degree elbow included angle, and 90 degree pronation of the hand), recorded EMG activity of the deltoid and triceps remained consistent across stable and unstable handle conditions whereas flexor and extensor activity increased as the handle became unstable (Bober, Kornecki, Lehr, & Zawadzki, 1982). This indicates that the flexor and extensor muscles were acting to stabilize the wrist when the handle itself was not stable (Bober, Kornecki, Lehr, & Zawadzki, 1982) and supports that off-axis forces (only present with the stable handle) help to reduce the external wrist moment. Further, in a majority of the tested cases (6 of 9) it was found that the wrist extensors were the first to initiate the task indicating that before muscles of the shoulder and elbow joints can produce force the wrist must be stable (Bober, Kornecki, Lehr, & Zawadzki, 1982). This further supports that theory that the wrist is the limiting joint of the upper extremity. Further, at submaximal test conditions the deltoid was the task initiator instead of the wrist extensors (Bober, Kornecki, Lehr, & Zawadzki, 1982). This indicates that at the lower force levels (40% and 60% of maximum) wrist stabilization was less important to task completion (Bober, Kornecki, Lehr, & Zawadzki, 1982) and may only be limiting at maximal force levels.

2.2.4 Allowance of Postural Adaptations during Manual Exertions

Numerous studies have examined postural adaptations during push and pull exertions. These studies have often focused on postural prediction based on different exertion conditions (handle heights, force level, standing or seated, dynamic or static, etc.) concluding that posture is an important predictor of force production at the hand. As such, posture may also contribute to off-axis force production. In particular, it has be noted that adjusting upper extremity postures have allowed subjects to increase push and/or pull efforts by engaging the torso through forward and/or backward leaning. During the sustained phase of maximal two-handed exertions, subjects adopted two arm postures, either with lightly flexed (0 to 15 degrees) or considerably flexed (50 to 90 degrees) elbows (Okunribido & Haslegrave, 2008). These changes occurred as force was built up to maximum during the trials (Okunribido & Haslegrave, 2008). Similarly, during standing two-handed, static push exertions at elbow height subjects tended to use either an elbow extended (greater than 90 degrees) or elbow flexed (less than 90 degree) posture (Hoffman, Reed, & Chaffin, 2011). Further, at low handle heights subjects tended to exert a larger total force in order to maintain an upright torso position (Hoffman, Reed, & Chaffin, 2011). In a different study, during one-handed, free position, full body push and pull exertions, subjects that were able to achieve closest to their maximum efforts adapted their postures (by leaning into the direction of force application) to employ more body weight when producing force (Wilkinson, Pinder, & Grieve, 1995). Similarly, during two-handed dynamic trolley pushing and pulling, observed changes in the vertical component of the hand force as floor friction was reduced corresponded with significantly less extension of the trunk relative to the pelvis (Boocock, Haslam, Lemon, & Thorpe, 2006). In a different study involving two-handed isometric pushes, participants modified their posture by adjusting the trunk flexion angle by changing the elbow flexion angle (Granata & Bennett, 2005). Again this postural change was shown to increase with increasing level of exertion from 15% body weight to maximum (Granata & Bennett, 2005).

2.3 Summary of and Gaps in Literature

As previously noted, many studies have observed the production of off-axis forces during manual pushing and pulling exertions. The issue is few studies have actually studied systematically what directly influences the occurrence of off-axis forces during these exertions. On the contrary, several theories exist as to why these forces may occur, even though it was not the main target of the studies. These include:

1. Off-axis forces were necessary to produce higher force in the on-axis direction (Grieve & Pheasant, 1981) (Seo & Armstrong, 2009) (Borgs & Hay, 1986) (Bober, Kornecki, Lehr, & Zawadzki, 1982).

2. Off-axis forces increased the vertical components of force in the downward direction to increase balance during dynamic standing and static pushing and pulling tasks (Hoffman, Reed, & Chaffin, 2011) (Boocock, Haslam, Lemon, & Thorpe, 2006) (Ciriello, McGorry, & Martin, 2001).

3. Off-axis forces allowed for targeted joint loading to reduce injury risk and/or compensate for limited joint strength (Granata & Bennett, 2005) (Hoffman, Reed, & Chaffin, 2008) (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000) (Seo & Armstrong, 2009). This observation was limited to the wrist and L5/S1 joints.

4. Off-axis forces changed as adopted postures changed to engage different muscle groups (Granata & Bennett, 2005) (Wilkinson, Pinder, & Grieve, 1995) (Hoffman, Reed, & Chaffin, 2011) (Okunribido & Haslegrave, 2008). In particular, they have been observed to increase forward lean to engage torso musculature and use body weight.

These observations have not been examined in a systematic way and thus have not been related to the production of off-axis forces in such a way that is useful for ergonomic design. Further, many of the observations have not been specifically tested (ie/ joint strength observations); rather they have been discussed abstractly and/or have been examined for one joint by use of a model. Influences of factors such as force level and/or posture have been evaluated with limited scenarios thus leaving a gap in the research and a gap in the applicability of the results to ergonomic design.

2.4 Novelty and Benefit of Study

The following study aimed to fill specific knowledge gaps in the literature and to present a systematic approach to evaluating the influences of off-axis forces on manual exertions related to ergonomic design. Particularly, it aspired to provide a systematic evaluation of the relationship between off-axis forces and force level. The study focused on a defined posture as well as a free posture so that separation of force and postural influences on off-axis force production were achieved. Further, the study was limited to force production via the upper extremity eliminating the influence of whole body balance and reducing the influences of other muscular systems (ie/ core and lower extremity). Finally, the study provided evaluation of joint moment trade-offs at the upper extremity to begin to quantify biomechanical influences of off-axis forces.

The major benefit of this study was a body of results that can be used by ergonomics to help guide design of workstations. As previously mentioned, not including off-axis forces in design is misrepresenting calculated working forces. Knowledge of how off-axis forces change with force level will guide when off-axis forces will have the greatest influence on calculated forces as well as when they should be considered in design.

III. Methodology

3.1 Participants

Eighteen right-hand dominant females with an mean age of 23 years (standard deviation (sd) 3.6 years), stature of 165 centimeters (cm) (sd 7.2 cm) and mass of 60.1 kilograms (kg) (sd 8.8 kg) were tested. Exclusion criteria included global body pain or discomfort within the past year and being left hand dominant.

3.2 Instrumentation

3.2.1 Motion Capture

Active motion capture of twenty-three reflective markers (12 millimetre (mm) diameter) was obtained using eight Vicon MX20 System cameras (Vicon, Oxford, UK) at a sampling frequency of 50 hertz. The markers were placed to track the position of the right hand, right forearm, right upper arm, and trunk. Marker placements were based on the International Society of Biomechanics (ISB) recommendations (Wu, et al., 2005).

Eleven markers were placed on bony landmarks at the thoracic spine eight (T8), cervical spine seven (C7), xiphoid process (XP), suprasternal notch (SS), right acromion (AC), medial epicondyle (ME), lateral epicondyle (LE), radial styloid (RS), ulnar styloid (US), second metacarpal (M2), and fifth metacarpal (M5); and three marker clusters were placed on the torso, right upper arm and right forearm (Figure 3.1).

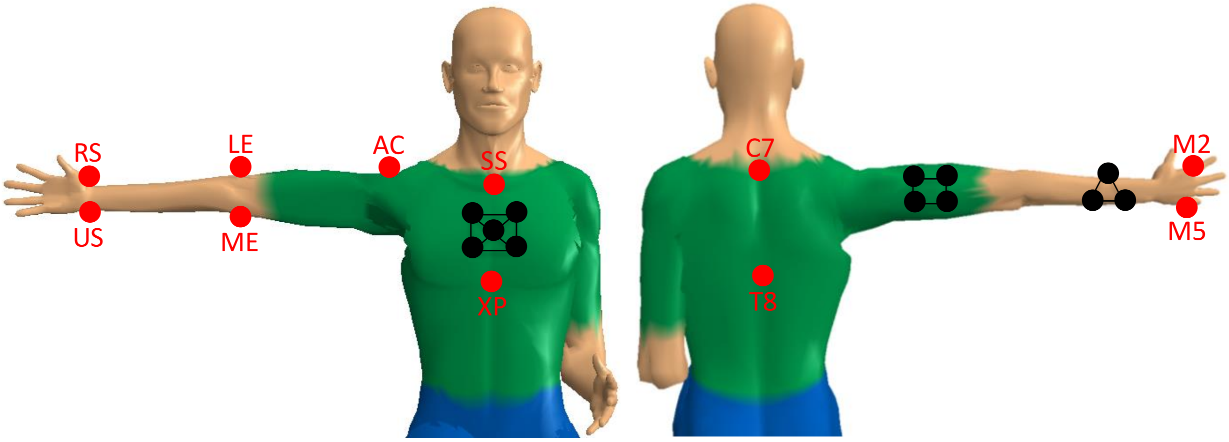

Figure 3.1 Marker (in red) and cluster (in black) placements for the right upper extremity

3.2.2 External Forces

External forces were measured using a MSA-6 transducer (AMTI, Watertown, MA, USA) rigidly secured to the Motoman HP50N robotic arm (West Carrollton, OH, US). The force cube was levelled at a height such that the middle of the cube was coincident with the subject's xiphoid process while they were seated in a stool and remained at this location throughout the entire experiment so that off-axis force production could be examined without the influence of changing the location of force application. All force was sampled at 50 hertz synchronously with the kinematic data.

Two different attachments to the force cube were used during the experiment. During the first half of the joint capacity testing, force was obtained using a padded, leather strap attachment (Figure 3.2).

Figure 3.2 Leather strap attachment for joint moment capacity testing

The leather strap attachment was chosen to measure force during joint capacity testing so that all force was directed along a straight line (the strap) and at an appropriate angle for each moment being tested (see Section 3.4.3 Joint Moment Capacity Testing). The strap had a padded contact surface (approximately 3 centimeters wide) to ensure discomfort was not strength limiting (Chaffin D. B., 1975).

For the remainder of the experiment, force was obtained using a force handle attachment positioned vertically, inline with the superior-inferior global axis (Figure 3.3).

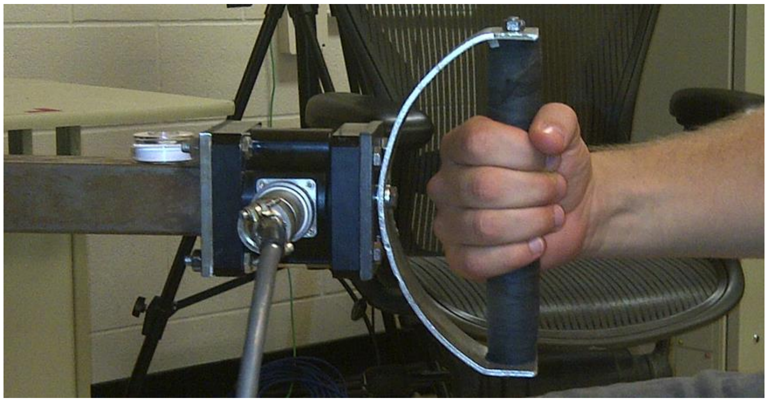

Figure 3.3 Force handle attachment for force exertions

The handle orientation was chosen to exaggerate the presence of off-axis force during exertions as it was found that handles which are deviated (not directly along the axis) in the longitudinal and horizontal planes enable more focused (higher on-axis force compared to off-axis force) hand exertions (Okunribido & Haslegrave, 2008). The contact, or grasping, surface of the handle was covered in hockey tape to increase comfort and friction so that they were not limiting factors in force production (Chaffin D. B., 1975).

3.2.3 Visual Feedback

A custom Labview program (National Instruments, Texas, USA) was used to give visual feedback of exertion level to participants (Figure 3.4).

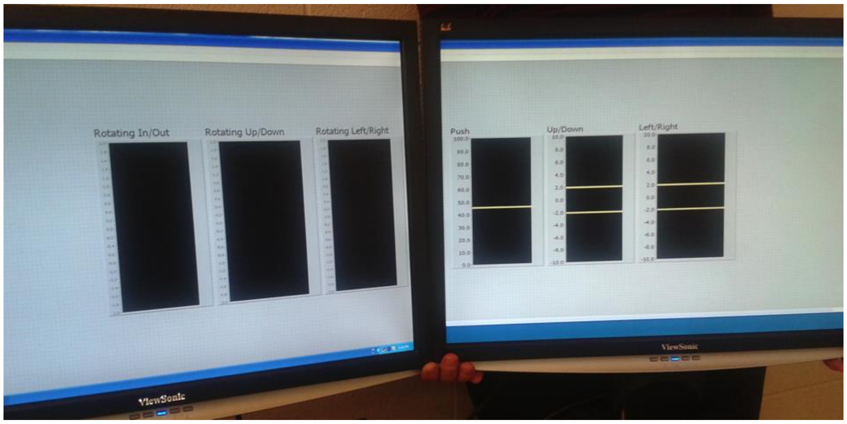

Figure 3.4 Visual display in Labview of condition without off-axis forces and moments

Depending on the experimental condition, participants were either given feedback of force and moment along the three principal axes or solely along the anterior-posterior (push-pull) axis. For conditions with off-axis forces, visual feedback was only given along the push-pull axis. For conditions without off-axis force, visual feedback was given of all forces and moments along all three principal axes. Force along the push-pull axis was displayed as a percentage of the maximum producible force along this axis during the posture unconstrained with off-axis forces condition. Force along the medial-lateral (left-right) and superior-inferior (up-down) axes was displayed in Newtons (N). Finally, all moments were displayed in Newton-meters (Nm).

3.2.4 Subject Posture

Subjects were limited to using only their upper limb when completing the experimental exertions. This was achieved by having the subjects seated in a stool and strapped to a wooden backboard attached to a rigid metal frame. There will be two Velcro straps, one across the chest similar to a seat belt and one across the lap (Figure 3.5).


[redacted]

Figure 3.5 Wooden backboard with stool and two Velcro strap attachments

In order to ensure the upper extremity was free to move and so that markers were occluded as little as possible, the backboard extended approximately three-quarters across the back (Figure 3.6). Even though it provided less support for the torso compared to a full width backboard, this sacrifice was necessary to ensure the scapular was free to move.

Figure 3.6 View of backboard from the rear to show coverage

Although being restrained as per above deviated from typical workplace postures, isolating the effect of upper extremity joint strength on force production was an important outcome of the study. Without these postural limitations the cause of off-axis force production would not be attributable directly to joint strength but to a combination of other effects. The backboard limited torso motion so that force production was isolated to the muscles of the upper extremity and the contribution of the core and back muscles was limited to stabilization. Further, during experimentation participants were instructed to maintain a stiff core and back, and to limit exertions to using only their upper extremity. Having the participants seated and strapped eliminated the effect of whole-body balance on force production and the variation of upper extremity postures chosen by subjects (Fischer S. L., 2011).

Except for constrained posture conditions, participants were allowed to choose their own upper extremity posture to produce the required exertion. It has been noted that required force level influences the posture chosen by subjects and that in a laboratory setting posture is biased when high-force exertions precede low-force exertions (Hoffman, Reed, & Chaffin, 2011). In fact, high-force level strategies are mimicked during low-force level exertions as a conservative strategy with regard to capability (Hoffman, Reed, & Chaffin, 2011). To avoid this adaptation, subjects were required to start and finish each exertion with their hand at their side, hanging in a relaxed fashion. Secondly, the submaximal trials were block randomized so that the order of exertion levels for each subject were not be the same, mitigating any possible order or fatigue effects.

3.3 Experimental Conditions

Four experimental conditions were evaluated:

1. Free posture with off-axis forces (FF)
2. Free posture without off-axis forces (FC)
3. Constrained posture with off-axis forces (CF)
4. Constrained posture without off-axis forces (CC)

Constraining posture allowed for the examination of how off-axis forces change when posture is constrained as per hypothesis three. It also allowed for the comparison of scaled moment distributions as they pertain to off-axis forces without the influence of postural differences between subjects as per hypothesis four. Constraining the production of off-axis forces allowed for direct comparison of the differences in maximum manual force as per hypothesis one. It also allowed for the comparison of off-axis force production at different submaximal force intensities as per hypothesis two. Finally, it allowed for the examination of the differences in joint strengths with and without off-axis force, as per hypothesis four.

3.3.1 Constrained Posture

During the constrained posture conditions, subjects were required to keep their upper extremity in a defined posture while they exerted the required intensity of force on the force handle. The posture was chosen based on two criteria:

1. The point of force application was not aligned with any joint center of the upper extremity (shoulder, elbow nor wrist), so that three-dimensional joints moments were produced at each joint.
2. The hand force was directed towards the midline of the torso to act as a safeguard against torso rotation.

The chosen posture was in the 60-degree shoulder plane of elevation (POE) (where 0 degrees is abduction and 90 degrees is flexion), at 30 degrees of upper arm elevation (ELV) (measured from the torso), at 100 degrees elbow included angle (ELB) (in flexion), and 140 degrees wrist included angle (WR) (in extension) (Figure 3.7). This posture was achieved while subjects maintained a functional grasp on the force handle.

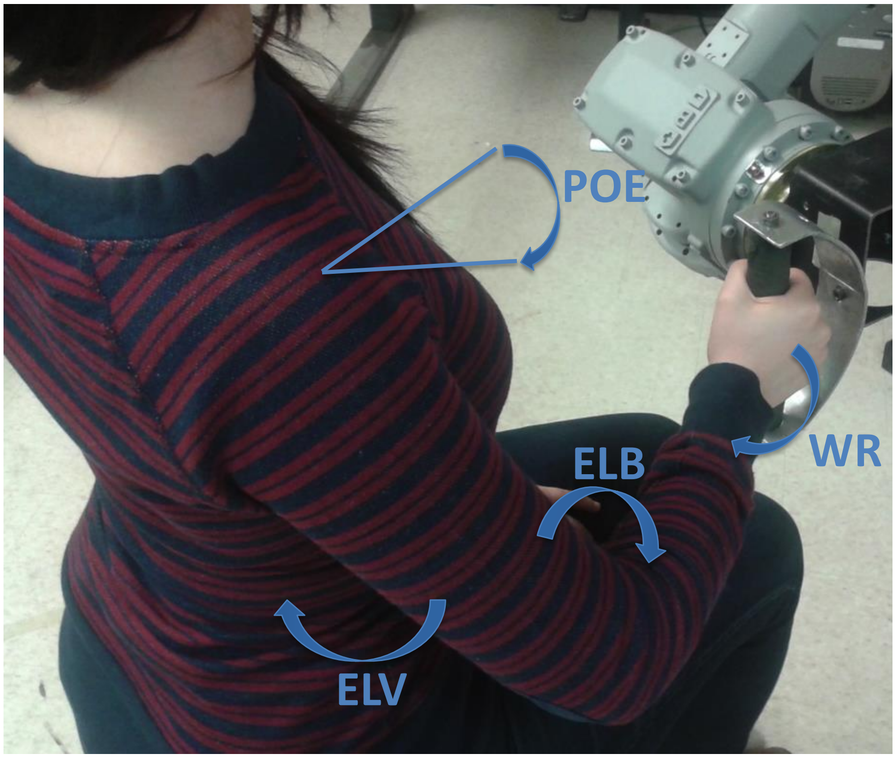

Figure 3.7 Constrained posture

Participants achieved this constrained posture first by grasping the force handle such that they could functionally exert force. Next, the defined joint angles were physically measured with a gynomometer and the stool, which the participants were seated in, was moved forward and backward until the upper extremity posture was achieved. To allow participants to move from the free to the constrained posture conditions, a retort stand was lined up with a dot (marked in permanent marker) on the side of participants' right elbow when they were in the constrained posture. Participants were instructed to touch but not lean on the retort stand during constrained posture conditions. The investigator monitored this during collections and during submaximal trials, would check (and adjust if necessary) the posture with a gynomometer.

3.3.2 With and Without Off-Axis Forces and Moments

As previously mentioned, (see Section 3.2.3 Visual Feedback) depending on which condition was being tested different amounts of visual feedback was provided to participants to allow them to complete the experimental conditions. During the conditions without off-axis forces, participants were instructed to keep the off-axis forces and all moments as close to zero as possible, with a maximum off-axis force threshold of +/-10% of the on-axis force level and maximum moment threshold of 2 Nm. Trials were repeated until this was achieved and only the trial that met the proper conditions was used for analysis.

The threshold for the off-axis force was chosen based on what is defined as static during maximum exertion testing (Chaffin D. B., 1975). The moment threshold was chosen because it was a low value during piloting. In fact, during piloting and experimentation, maintaining moment values as close to zero as possible while keeping off-axis forces as close to zero as possible was not difficult (see Table 4.8). Further, post experimentation, the off-axis force and moment data was examined and the thresholds were adjusted to better represent the data (see Section 4.1.3 Off-Axis Force and Moment Variation).

3.4 Experimental Protocol

In total participants performed unilateral, manual pushes and pulls with their right hand, on a force handle at a location parallel to their xiphoid process, at one maximal and ten submaximal force levels, and in four different conditions. This yielded a total of eight maximal trials and eighty submaximal trials (Figure 3.8). Prior to this participants performed a series of maximal joint capacity exertions in a seated position and a training protocol (Figure 3.8).

Participant signed consent form and learned about experiment

Set-up force handle

- Placed force handle coincident to participant's xiphoid process while they were seated
- Calibrated force cylinder and Labview program
- Placed participant in constrained posture and positioned retort stands

Participant Screening and Training

- Introduced Labview program and explained conditions
- Screened participants to ensure they could complete exertions
- Allowed practice producing exertion types at different force levels

Completed joint capacity testing protocol

- Two rounds of 5 second trials
- At least 2 minutes rest between trials, more if needed

Collection of participant information

- Gender, age, height and weight

Set-up motion capture

- Adhered reflective markers and marker clusters onto participants
- Collected calibration trial in anatomical position

Placed participant in experimental posture

- Ensured participant could still obtain constrained posture based on retort stands and adjusted if necessary
- Moved backboard into place and strapped participant to backboard

Maximal Exertions

- Completed 1 round of randomized maximal push and pull exertions in the 4 experimental conditions
- At least 2 minutes rest between trials, more if needed

Submaximal Exertions

- Completed 1 round of randomized scaled submaximal push and pull exertions in the 4 experimental conditions
- Allowed participant to take necessary rest
- Maximum force testing to judge fatigue every 20 trials

Experimental wrap up and thank you letter

Figure 3.8 Experimental outline

The following sections outlined the details of the aforementioned experimental procedure.

3.4.1 Calibration Trials

Prior to data collection, calibration trials were collected. The first was a one second, stationary trial where subjects stood in anatomical position and all markers were showing. This trial was collected so that markers occluded during the experiment could be relocated during data processing based on the position relative to the marker clusters. Next, zero force and shunt force trials were collected with the strap on the force cube. Finally, zero force and shunt force trials were collected with the handle on the force cubes. These trials were collected so that voltage data from the force strap and handle could be converted to force in Newtons during data analysis.

3.4.2 Training Procedure

Prior to experimentation, a training period was completed by each of the participants so they could practise meeting each of the required conditions. The investigator, with input from the participant, judged whether or not enough practise had been allotted. Generally, training was complete when the participant was able to achieve the required condition and maintain it for at least five seconds.

It was noted during piloting that as the required force increased, meeting the conditions was more difficult. As such, subjects would start by practising at lower force levels, then would practise at higher force levels as they got better at meeting the experimental conditions.

Training was necessary for many reasons. The first was that it is important the manual exertions be achieved quickly when required and maintained as steadily as possible so that they are representative of the participants' motions. Visual feedback was used to help participants achieve the conditions without off-axis force. Being able to use this visual feedback takes time to learn; training allowed for this learning. A guide was used to help participants achieve the constrained posture conditions. The participants were trained to maintain the constrained posture without "leaning on" or using the guide to help with the exertion, as well as to exert the required force levels while not moving their arm from the defined posture. Finally, participants learnt how to exert force with just the use of the upper extremity. Participants used the training period to practise using the backboard but not as an assistant to the exertion, and to practise maintaining a stiff core so that the upper extremity could be isolated.

3.4.3 Joint Moment Capacity Testing

In order to compare moment capacity across different joints of the upper extremity, the moments were scaled to the maximum capacity of that joint. Further, representing the joint moments as scaled values allowed for a better understanding of which moments were limiting to the exertions. As such, prior to collection, the maximum joint moment capacity was collected for the three joints of the upper extremity. Total moments about the three joints were divided into seven moments about each of the anatomically relevant axes for the right upper extremity (Wu, et al., 2005) (Table 3.1).

Table 3.1 Seven joint moments with sign convention and corresponding joints

Joint	Moment
Shoulder	Flexion (+)/Extension (-)
	Abduction (+)/Adduction (-)
	Internal Rotation (+)/External Rotation (-)
Elbow	Flexion (+)/Extension (-)
	Supination (-)/Pronation (+)
Wrist	Flexion (+)/Extension (-)
	Radial Deviation (-)/Ulnar Deviation (+)

Each maximal exertion was repeated at least twice, yielding a total of twenty-eight exertions, with a two-minute break between each trial to avoid fatigue (De Luca, 1997) (Chaffin D. B., 1975) (Caldwell, et al., 1974). If the investigator and/or the participant noted that the exertion was not completed correctly, such as the upper extremity was in the wrong position or the force was exerted in the wrong direction, the trial was repeated and only the correct trial analyzed.

Each moment trial was collected for five seconds. The participants were instructed to "ramp up" without "jerking" to their maximum and "hold" this force level until the trial was collected (Chaffin D. B., 1975) (De Luca, 1997) (Caldwell, et al., 1974). Verbal encouragement was used to ensure the participants were producing maximum exertions (Fischer, Belbeck, & Dickerson, 2010). For the shoulder moments, and elbow flexion and extension moments, the strap attachment was used (see Section 3.2.2 External Forces). For the wrist moments, and elbow supination and pronation moments, the handle attachment was used (see Section 3.2.2 External Forces). The strap and/or force handle was placed distal to the joint of interest (see Appendix A for specific locations). Moment arms were measured by the investigator using a tape measure and were from the joint centre of interest, perpendicular to the axis of rotation of the moment, to the location where the strap and/or force handle was in contact with the participant.

3.4.4 Force Levels for Exertions

Two types of force levels were obtained during the experiment: maximal and submaximal. The maximal exertions were obtained first so that the submaximal exertions could be scaled to them.

3.4.4.1 Maximal Exertions

One round of maximal exertions was collected in random order. This included a maximum for each of the four conditions once for pushing and once for pulling, yielding a total of eight maximal exertions. To avoid fatigue, at least two-minutes of rest was given between each trial (De Luca, 1997) (Chaffin D. B., 1975) (Caldwell, et al., 1974) and participants were given the option for more rest if they needed. Maximum trials were not repeated as it was determined that sixteen trials would be too fatiguing for participants which would alter the results of the remainder of the experiment. Even with only eight maximum trials, it was found that participants required additional rest prior to commencing the second part of the experiment.

For the conditions with off-axis forces, participants were instructed to increase (without "jerking") their force exertion to the maximum they could achieve and hold it until the five second trial was finished recording (Chaffin D. B., 1975) (De Luca, 1997) (Caldwell, et al., 1974). For the conditions without off-axis forces, participants were given unlimited time to achieve they highest possible force they could. Once they felt they had achieved this, the trial was complete. If at any time the participant and/or investigators(s) felt that the conditions were not met during the trial, the trial was repeated and only the correct result used during analysis. Finally, during all maximum trials, both visual feedback of force level (see Section 3.2.3 Visual Feedback) as well as verbal encouragement was given to ensure the participants were producing maximum forces (Fischer, Belbeck, & Dickerson, 2010).

3.4.4.2 Submaximal Exertions

One round of submaximal exertions was collected in random order. This included an exertion at each of the submaximal force levels for each condition for both pushing and pulling, yielding a total of eighty submaximal exertions. Fatigue was less of a concern during the submaximal trials but for some participants was still present. It was noted that as the participants began to fatigue, their ability to achieve the experimental conditions decreased. When this occurred, additional rest was given to participants until they felt ready to continue the experiment. Further, to ensure fatigue was not present, after every twenty trials participants were instructed to exert maximum force in the push and pull direction with no other conditions and reach their previously obtained maximum. If this was not achieved, participants rested until this maximum was obtainable then continued the experiment.

Visual feedback of the required force level as well as verbal encouragement (Fischer, Belbeck, & Dickerson, 2010) was used to ensure the participants were producing forces at the required levels and maintaining these levels over the duration of collection. Participants were instructed to meet the required force level (matching to the visual feedback) for each trial and then inform the investigator when they had achieved the trial requirements (required force level and conditions). Once informed, the investigator recorded the exertion for three seconds and the trial was complete. If at any time during the trial it was noted that the required force level and/or condition requirements for the trial had been compromised, the trial was repeated and only the correct trial was used during analysis.

The required submaximal force levels were below 50% of the maximum force in the unconstrained posture with off-axis force condition. This represents levels at which people work; thus, changes in off-axis forces at these levels would be important for ergonomic design. An even spacing of force levels was be tested in this range from 0% to 50% at increments of 5% so that a good representation of changes in this range was obtained. Further, it is known that forces produced during unconstrained tasks are larger than forces produced when off-axis forces are constrained (Grieve & Pheasant, 1981). Thus, prior to experimentation these force levels were piloted to ensure it was possible for participants to produce the higher submaximal forces when the off-axis forces were constrained. During piloting, it was found that 40% to 50% of the unconstrained maximum was difficult to achieve without off-axis forces, but attainable and anything above 60% of the unconstrained maximum was nearly impossible to achieve without off-axis forces.

3.5 Data Analysis

3.5.1 Filtering

All data was filtered using a dual pass, second order Butterworth filter with a cut-off frequency of 6 Hz (Dickerson, Martin, & Chaffin, 2006). This cut-off frequency was used because human motion rarely exceeds this value (Winter, 2009). The same filter was applied to both the position and force data so that all raw data was treated the same way during processing.

3.5.2 Hand Force Data

All hand force data was processed using custom Matlab programs. All force data was converted to Newtons from voltage using the zero and shunt values obtained during the calibration trials. A linear relationship was used to convert the outputted voltage from the force transducer to the force values in Newtons.

3.5.2.1 Maximum Force

As per Hypothesis 1, only the maximum force along the push and pull axis was analyzed. In order to average force across participants and reduce intra-participant variability, all maximum force data was represented as percent body weight in Newtons.

For the free force conditions (FF and CF), the raw voltage output from the push and pull channels (force along the z-axis) was first filtered. Next, the maximum value from the whole trial was found. Finally, this value was converted to Newtons and represented as percent body weight.

For the without off-axis force conditions (FC and CC), the raw voltage output from the on- and off-axis channels (force along the x-, y- and z-axes) were first filtered and converted to Newtons. Next, the off-axis forces were scaled to percent of the on-axis force. A search was then performed on the data so that only on-axis force produced while the scaled off-axis forces were between -20% and +20% was extracted. Finally, the maximum value of on-axis force meeting this condition was found and represented as a percent of body weight.

3.5.2.2 Submaximal Force

For all submaximal exertions, the data was first windowed so that it did not include transient periods near the beginning and end of the trial (Caldwell, et al., 1974). Of the three seconds of collected data (total of 150 frames of data), the first and last half seconds of data (25 frames at the beginning and end of the trials) were not processed. Next, the windowed data was filtered and averaged to obtain three values of force from the on- and off-axis channels (force along the x-, y- and z-axes). Finally, to be able to average force across participants and reduce intra-participant variability, the off-axis forces from each trial were represented as a percent of the on-axis force.

3.5.3 Maximum Joint Moment Capacity

All maximum joint moments were processed using custom Matlab programs. For moments that were measured using the strap attachment, the raw voltage output from all three channels (force along the x, y and z-axes) was filtered and converted to Newtons. Next, the resultant force along the strap was calculated and multiplied by the measured moment arm to obtain the moment produced across the entire trial in Newton-meters. Similar, for the wrist flexion-extension and radial-ulnar deviation moments, raw voltage output was taken from the channel corresponding to force along the y-axis and x-axis of the force cube, respectively, filtered and converted to Newtons. Next, the force in Newtons was multiplied by the measured moment arm to obtain the moment produced across the entire trial in Newton-meters. For elbow supination-pronation, the raw voltage output was taken from the channel corresponding to the moment about the z-axis, filtered and converted to Newton-meters. Next, each of these moments were added to or subtracted from (depending on the direction of the moment) the moment due to gravity of all segments distal to the joint of interest. Finally, the maximum moment about each anatomically relevant axis for the right upper extremity was obtained and used to scale the moments in the submaximal trials.

3.5.4 Joint Angles and Moments

First using the Vicon Nexus software (Vicon, Oxford, UK) occluded markers from each trial were pattern filled and the data was exported. Next, the data was imported into Visual 3D (C-motion, Germantown, Maryland, USA) and filtered. A template was created to calculate the joint angles and moments based on the calibration trial collected at the beginning of the experiment and was applied to all trials that joint angles and moments were required for (all maximal and submaximal trials in the constrained posture).

The template developed In Visual 3D defined all joint centers and local coordinate systems based on ISB standards. Joint centers were defined for the shoulder (glenohumeral joint), elbow and wrist joints. The shoulder joint center was located 60 millimeters (mm) below the acromial process along the negative vertical axis of the trunk (Nussbaum & Zhang, 2000). The wrist and elbow joint centers were defined as the midpoint between the markers placed on the radial and ulnar styloid, and the lateral and medial epicondyle, respectively (Wu, et al., 2005). Finally, local coordinate systems for the thorax, upper arm, forearm, and hand were defined as part of the template in Visual 3D (Table 3.2, Figure 3.3).

Table 3.2 Summary of defined local coordinate systems (Wu, et al., 2005)

Segment	X-Axis	Y-Axis	Z-Axis
Thorax	Cross product of y- and z-axes pointing anteriorly (medial-lateral bending)	Midpoint between 8th thoracic vertebra and xiphoid process, and 7th cervical vertebra and sternal notch, pointing proximally (axial rotation)	Line perpendicular to the plane formed by sternal notch, 7th cervical vertebra, and midpoint between 8th thoracic vertebra and xiphoid process, pointing laterally (flexion-extension)
Upper Arm	Cross product of y- and z-axes, pointing anteriorly (abduction-adduction)	Line connecting shoulder joint center to elbow joint center, pointing to shoulder joint center (axial rotation)	Line perpendicular to the plane formed by y-axis of humerus and y-axis of forearm, pointing laterally (flexion-extension)
Forearm	Line perpendicular to the plane through ulnar styloid, radial styloid, and elbow joint center, pointing anteriorly (supination-pronation)	Line connecting ulnar styloid to elbow joint center, pointing proximally	Cross product of x- and y-axes, pointing laterally (flexion-extension)
Hand	Cross product of y-axis and the plane defined by 2nd and 5th metacarpal, and wrist joint center, pointing anteriorly (radial-ulnar deviation)	Midpoint between 2nd and 5th metacarpal, and wrist joint center, pointing proximally	Cross product of x- and y-axes, pointing laterally (flexion-extension)

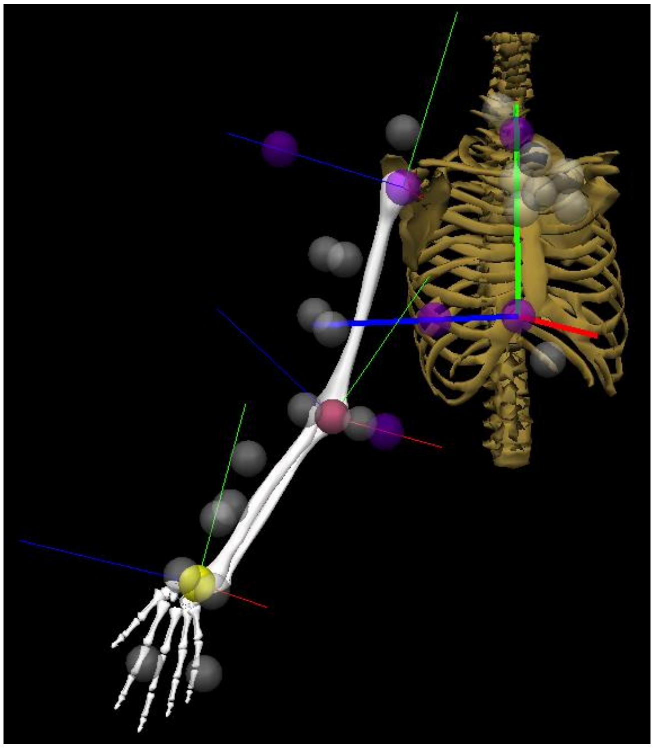

Figure 3.9 Local coordinate systems for each segment (red = x-axis, green = y-axis, blue = z-axis)

Only four joint angles were calculated using Visual 3D since the constrained posture required monitoring of these angles throughout the experiment. These included shoulder plane of elevation (POE) where 0 degrees was abduction and 90 degrees was flexion; upper arm elevation (ELV) measured from the torso thus always negative; elbow included angle (ELB) where flexion was positive and hyperextension was negative; and wrist included angle (WR) where flexion was positive and extension was negative (Wu, et al., 2005). The joint angles were calculated in Visual 3D based on Cardan rotation sequences for each joint. The rotation sequence for the shoulder joint was YXY (upper arm relative to thorax), for the elbow joint was ZXY (forearm relative to upper arm), and for the wrist joint was ZXY (right hand relative to forearm) (Wu, et al., 2005). Of these nine rotations, shoulder plane of elevation corresponded to the first Y rotation at the shoulder joint, shoulder elevation corresponded to the X rotation at the shoulder joint, elbow included angle corresponded to the Z rotation at the elbow joint, and wrist included angle corresponded to the Z rotation at the wrist joint (Wu, et al., 2005) (Morrow, Hurd, Kaufman, & An, 2010).

In comparison, joint moments were calculated at the three joints of the right upper extremity: wrist, elbow and shoulder. The net joint moments were calculated about the joint centers and were relative to the proximal segment. Similar to the joint angles, the net joint moments were resolved in the Cardan rotation sequences for each joint (see previous paragraph). Seven joint moments were calculated for the three joints and these corresponded to specific anatomically relevant rotations (Table 3.3).

Table 3.3 Joint moment resolution systems based on Cardan rotation sequences (Morrow, Hurd, Kaufman, & An, 2010)

Joint	Rotation	Anatomical Definition and Direction	
Shoulder	first Y rotation	Flexion (+)	Extension (-)
	X rotation	Abduction (+)	Adduction (-)
	second Y rotation	Internal Rotation (+)	External Rotation (-)
Elbow	Z rotation	Flexion (+)	Extension (-)
	Y rotation	Supination (-)	Pronation (+)
Wrist	Z rotation	Flexion (+)	Extension (-)
	X rotation	Radial Deviation (-)	Ulnar Deviation (+)

In order to calculate joint moments, the external force vector obtained from the force handle (including all force and moment) was inputted into Visual 3D. The external force and moments were oriented in the global coordinate system and applied to the hand at the center of gravity. Prior to input, external moments about the x- and y-axis of the force cube were calculated about the center of gravity of the hand based on the moment arm produced by the force handle (Greig & Wells, 2004). Finally, segment weights and locations of segment center of gravities were determined as fractions of subject mass and segment length (defined from joint center to joint center), respectively. These were based on literature and chosen to specifically correspond to a female population (de Leva, 1996).

The joint angle and moment data was calculated for each frame of the trial and exported from Visual 3D. For the maximal trials, only the joint angle data was used and the angles that corresponded to the frame in which the maximum on-axis force occurred were extracted using Matlab. For submaximal trials, both the joint angle and moment data was used. For the submaximal joint angles, the data was windowed same as the force data and averaged across this window. For the submaximal joint moments, the data was windowed same as the force data, averaged across this window and scaled so that each moment was a percent of the previously determined joint moment capacity.

3.5.5 Statistical Analysis

Statistical analysis was performed using SAS 9.2 TS Level 2M0 (SAS Institute Inc., NC, USA). This program was used because it can properly analyze data with missing data points without removing whole participant data from the analysis. This was important since not all participants achieved all experimental conditions and no data filling was conducted for the missing data points.

For the maximal on-axis force data, one-way repeated measures analysis of variance (ANOVA) was performed on the data. The independent variable was condition (four conditions: FF, FC, CF and CC) and the dependent variable was the maximum on-axis force produced in percent of body weight (% BW) (Table 3.4).

For the submaximal force and moment data, a series of two-way repeated measures analysis of variance (ANOVA) were performed on the data with each direction of off-axis force (x and y) and each joint moment being analyzed separately. The independent variables were condition (two conditions either: FC to FF, CF to FF or CC to CF) and force (ten required submaximal levels: 5% of maximum on-axis force in the FF condition (% max) to 50% max by increments of 5% max) and the dependent variable was off-axis force in percent of on-axis (% on-axis), or joint moment in percent of maximum joint moment capacity (% cap) (Table 3.4). For all data, main effects and interactions were examined but no statistical relationships were drawn between push and pull exertions as they were analyzed separately. All significance levels (p) were set to less than 0.05 and a post-hoc Tukey honest significance difference (HSD) test was used to correct for any type I error that may have been present in the data.

Table 3.4 Summary of statistical analyses performed

Hypothesis	Independent Variable	Dependent Variable(s)	Analysis
1	Condition: FF, FC, CF, CC	Maximum on-axis force (%BW)	One-way repeated measures ANOVA
2	1. Condition: FC, FF 2. Submaximal force level (5% to 50% max)	Off-axis force (% on-axis)	Two-way repeated measures ANOVA
3	1. Condition: CF, FF 2. Submaximal force level (5% to 50% max)	Off-axis force (% on-axis)	Two-way repeated measures ANOVA
4 (force)	1. Condition: CC, CF 2. Submaximal force level (5% to 50% max)	Off-axis force (% on-axis)	Two-way repeated measures ANOVA
4 (moment)		Moment (% cap)	Two-way repeated measures ANOVA

IV. Results

The first four sections pertain to the results for each specific hypothesis and the final section describes how precisely each experimental condition was met.

4.1 Hypothesis 1

Evaluating hypothesis 1 required comparison of the maximum on-axis force across all four experimental conditions: free posture with off-axis force (FF), free posture without off-axis force (FC), constrained posture with off-axis force (CF), and constrained posture without off-axis force (CC).

For the maximum pushing exertions, the free posture with off-axis force condition (FF) and the constrained posture without off-axis force condition (CC) were significantly different from all other conditions and each other. The free posture without off-axis force condition (FC) and the constrained posture with off-axis force condition (CF) were significantly different from all other conditions and not significantly different from each other (Table 4.1, Figure 4.1).

Table 4.1 Average maximum on-axis force, standard deviation and statistical results for maximum pushing exertions (* indicates statistical significance)

Condition	Mean maximum on-axis push force (% Body Weight (BW))	sd (% BW)	n	F	p	Tukey Grouping
FF	18.4	3.0	18	$F_{3,71} = 40.57$	p = <0.0001*	A
FC	12.3	2.0				B
CF	14.3	3.3				B
CC	10.1	1.8				C

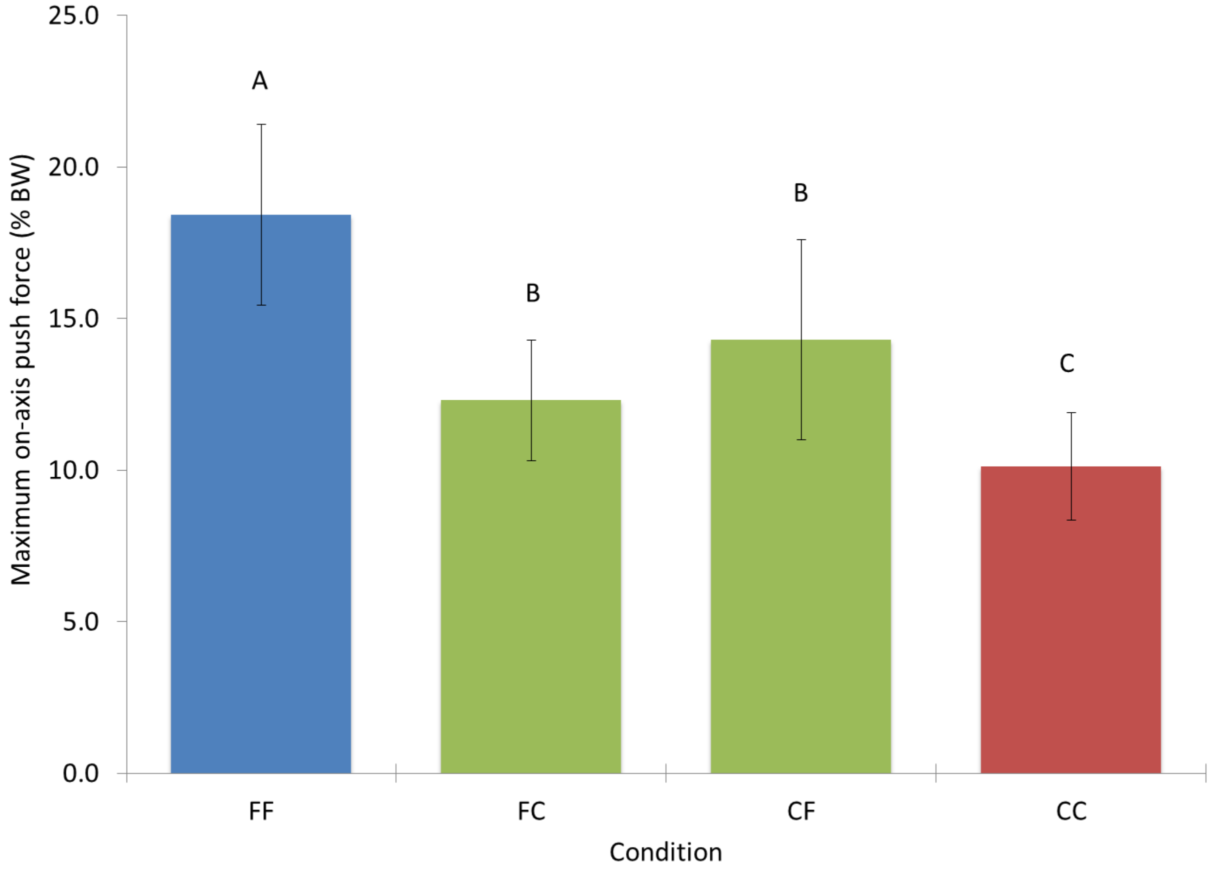

Figure 4.1 Mean maximum on-axis force along the push-pull axis during maximum pushing exertions for each condition. Different letters and colouring indicate statistically different levels according to Tukey post-hoc analysis. As the conditions became more constrained, the maximum on-axis force decreased. There was no statistical difference between not allowing off-axis force and constraining posture.

The highest on-axis force was produced during the FF condition and the second highest during the FC and CF conditions. The lowest maximum on-axis force was produced during the CC condition.

For maximum pulling exertions, the FF condition and the CF condition were significantly different from all other conditions and each other. The FC condition and the CC condition were significantly different from all other conditions and not significantly different from each other (Table 4.2, Figure 4.2).

Table 4.2 Average maximum on-axis force, standard deviation and statistical results for maximum pulling exertions (* indicates statistical significance)

Condition	Mean maximum on-axis pull force (% BW)	sd (% BW)	n	F	p	Tukey Grouping
FF	-27.6	6.0	18	$F_{3,71}$ = 27.69	p = <0.0001*	A
FC	-18.8	4.5				C
CF	-23.6	3.8				B
CC	-15.8	3.8				C

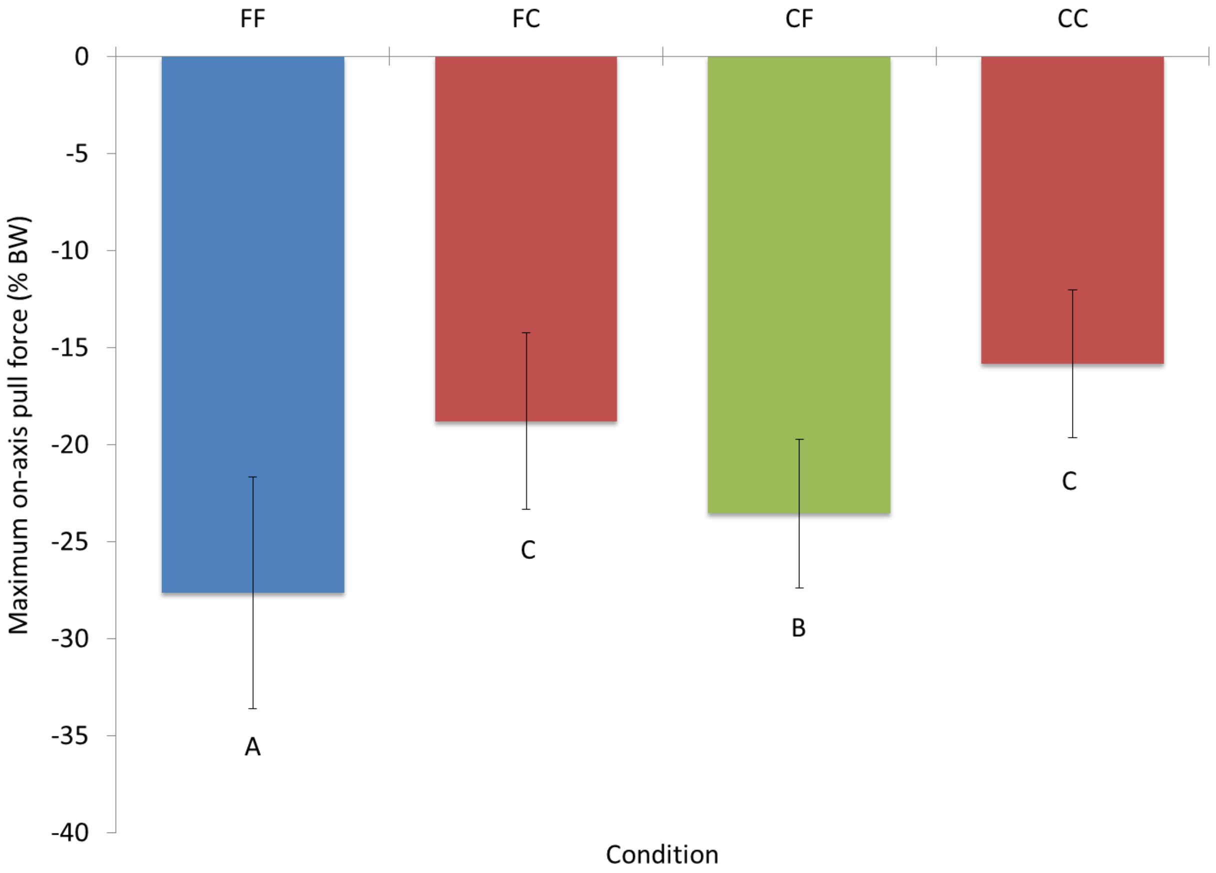

Figure 4.2 Mean maximum on-axis force along the push-pull axis during maximum pulling exertions for each condition. Different letters and colouring indicate statistically different levels according to Tukey post-hoc analysis. As the conditions became more constrained, the maximum on-axis force decreased. This was not as significant as during pushing exertions since constraining posture only was significantly higher than constraining force only. There was no statistical difference between the two conditions without off-axis force.

The highest on-axis force was produced during the FF condition and the second highest during the CF condition. For both conditions without off-axis forces (FC and CC), the lowest maximum on-axis force was observed.

4.2 Hypothesis 2

Evaluating hypothesis 2 required comparison of the free posture without off-axis force condition (FC) to the free posture with off-axis force condition (FF) across all required submaximal force levels for force along each of the off-axes (up-down and left-right).

For pushing exertions, there was a condition*force interaction for off-axis force along the up-down axis (Table 4.3).

Table 4.3 Statistical significance for force along the up-down axis when comparing FC to FF across submaximal force levels during pushing (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
FC to FF, up-down	Condition	$F_{1,17} = 0.00$	p = 0.9687
	Force	$F_{9,153} = 1.51$	p = 0.1486
	Condition*Force	$F_{9,143} = 2.46$	p = 0.0122*

When off-axis force was constrained there was a slight decrease in upward off-axis force, whereas when off-axis force was allowed there was an increase from downward to upward off-axis force (Figure 4.3, Table B.1 in Appendix B). These rates of change were significantly different from each other and the difference between the required force level of 5% max and 50% max was 1.7% on-axis when off-axis force was constrained and 8.9% on-axis when off-axis force was not constrained. This indicates that when off-axis force was constrained the rate of change was close to zero, compared to when it was not constrained the upward off-axis force increased as submaximal force increased. Further, off-axis force was never significantly different between the two conditions; as such the difference in rates of change did not correspond with the direction of pushing within the tested submaximal force range.

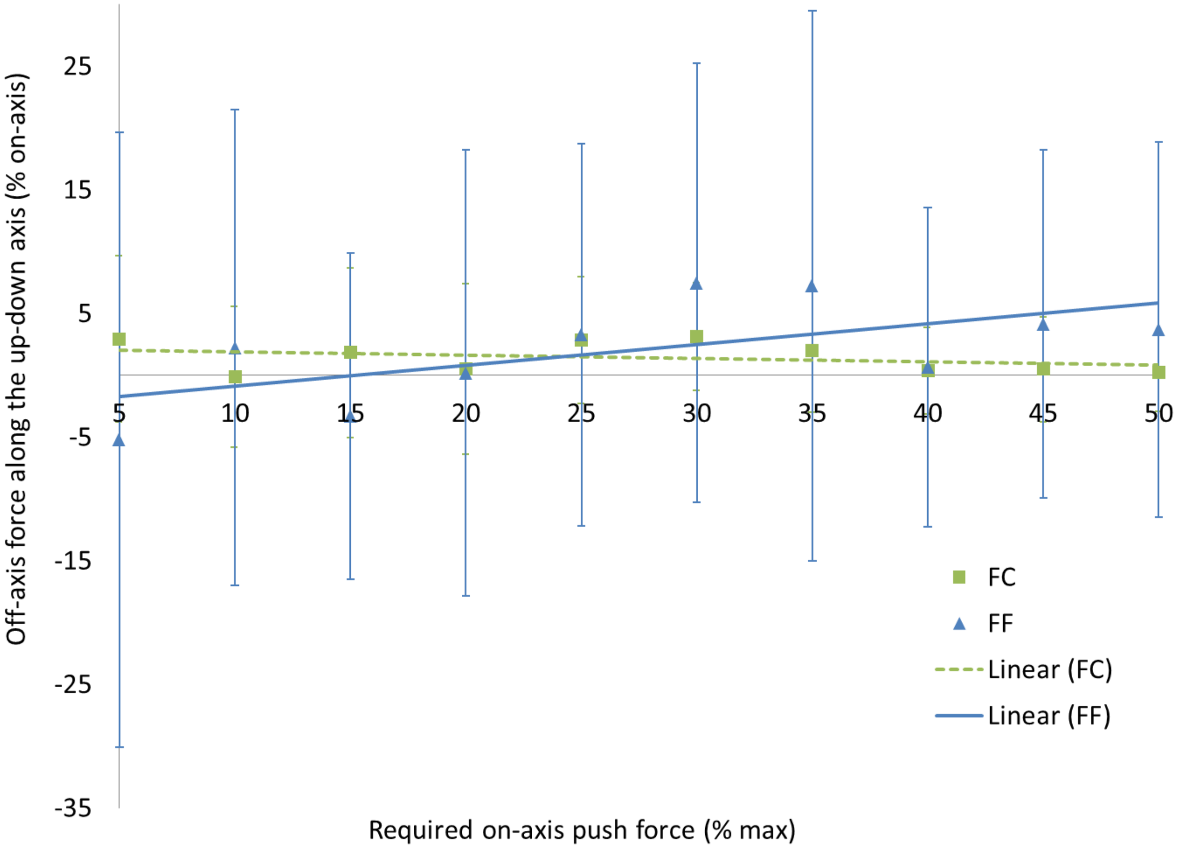

Figure 4.3 Off-axis force along the up-down axis during submaximal push exertions for the free posture without (green, dotted line) and with (blue, solid line) off-axis force. The rate of change of off-axis force was significantly different between the two conditions. This rate was nearly zero when off-axis force was allowed and when off-axis force was not allowed, as required submaximal force increased upward off-axis force also increased. Note: lines are for illustrative purposes.

There was a main effect of condition for off-axis force along the left-right axis (Table 4.4).

Table 4.4 Statistical significance for force along the left-right when comparing FC to FF across submaximal force levels during pushing (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
FC to FF, left-right	Condition	$F_{1,17} = 12.58$	p = 0.0025*
	Force	$F_{9,153} = 1.09$	p = 0.3720
	Condition*Force	$F_{9,143} = 1.11$	p = 0.3575

When off-axis force was allowed, there was significantly more leftward off-axis force compared to when it was not allowed (Figure 4.4, Table B.1 in Appendix B). This difference was consistent across all required submaximal force levels. The average off-axis force along the left-right axis for the without off-axis force condition was -3.1% on-axis (sd 5.9% on-axis n = 172) and for the with off-axis force condition was -8.7% on-axis (sd 11.9% on-axis n = 178), which was a difference of 5.6% on-axis.

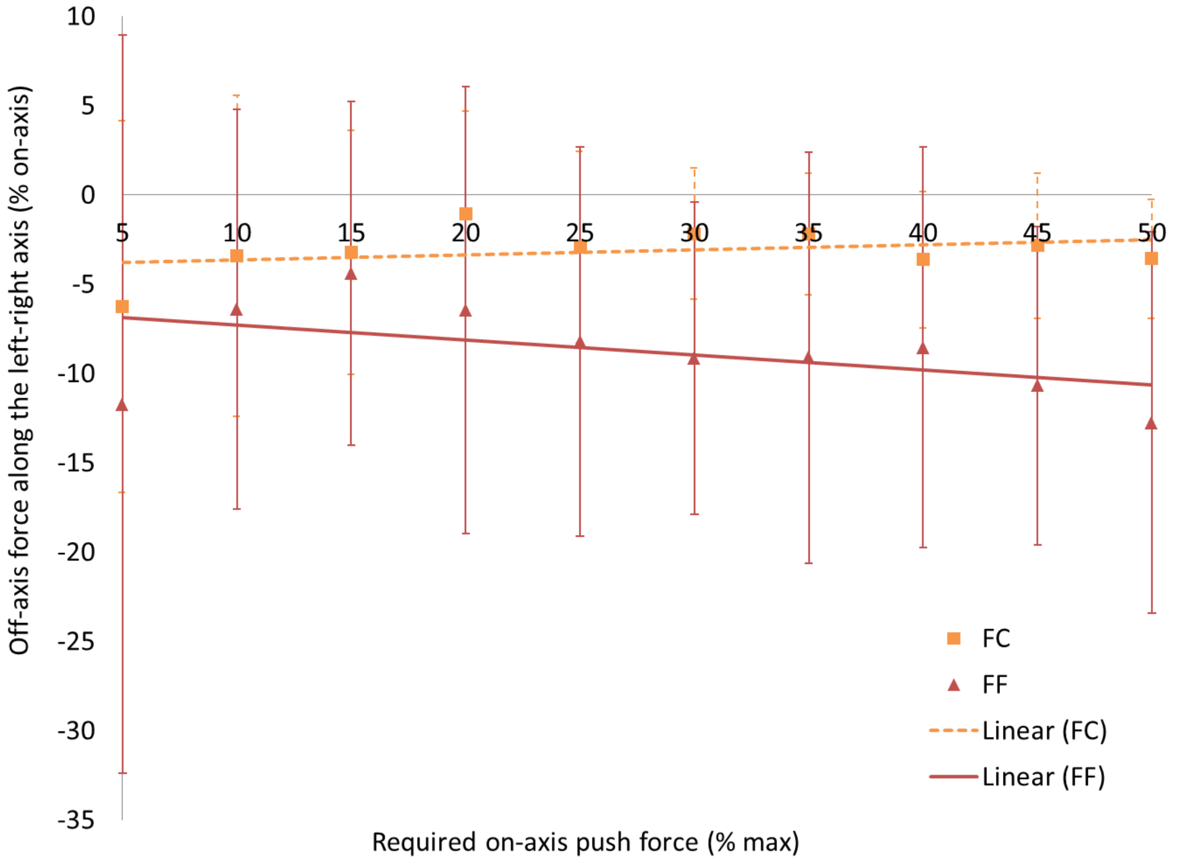

Figure 4.4 Off-axis force along the left-right axis during submaximal push exertions for the free posture without (orange, dotted line) and with (red, solid line) off-axis force. There was more leftward off-axis force when off-axis force was allowed compared to when it was not. The difference was consistent at 5.6% on-axis. Note: lines are for illustrative purposes.

For pulling exertions, there were condition and force main effects for off-axis force along the up-down axis (Table 4.5).

Table 4.5 Statistical significance for force along the up-down axis when comparing FC to FF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
FC to FF, up-down	Condition	$F_{1,17} = 29.78$	p = <0.0001*
	Force	$F_{9,153} = 2.22$	p = 0.0237*
	Condition*Force	$F_{9,149} = 1.77$	p = 0.0778

When off-axis force was allowed, there was significantly more downward off-axis force compared to when it was not allowed (Figure 4.5, Table B.2 in Appendix B). Further, for both conditions, as the required submaximal force level increased the downward off-axis force decreased and got closer to zero. The average off-axis force along the up-down axis for the with off-axis force condition was -2.4% on-axis (sd 4.3% on-axis n = 176) and for the without off-axis force condition was -15.0% res (sd 14.2% res n = 180), which was a difference of 12.6% on-axis.

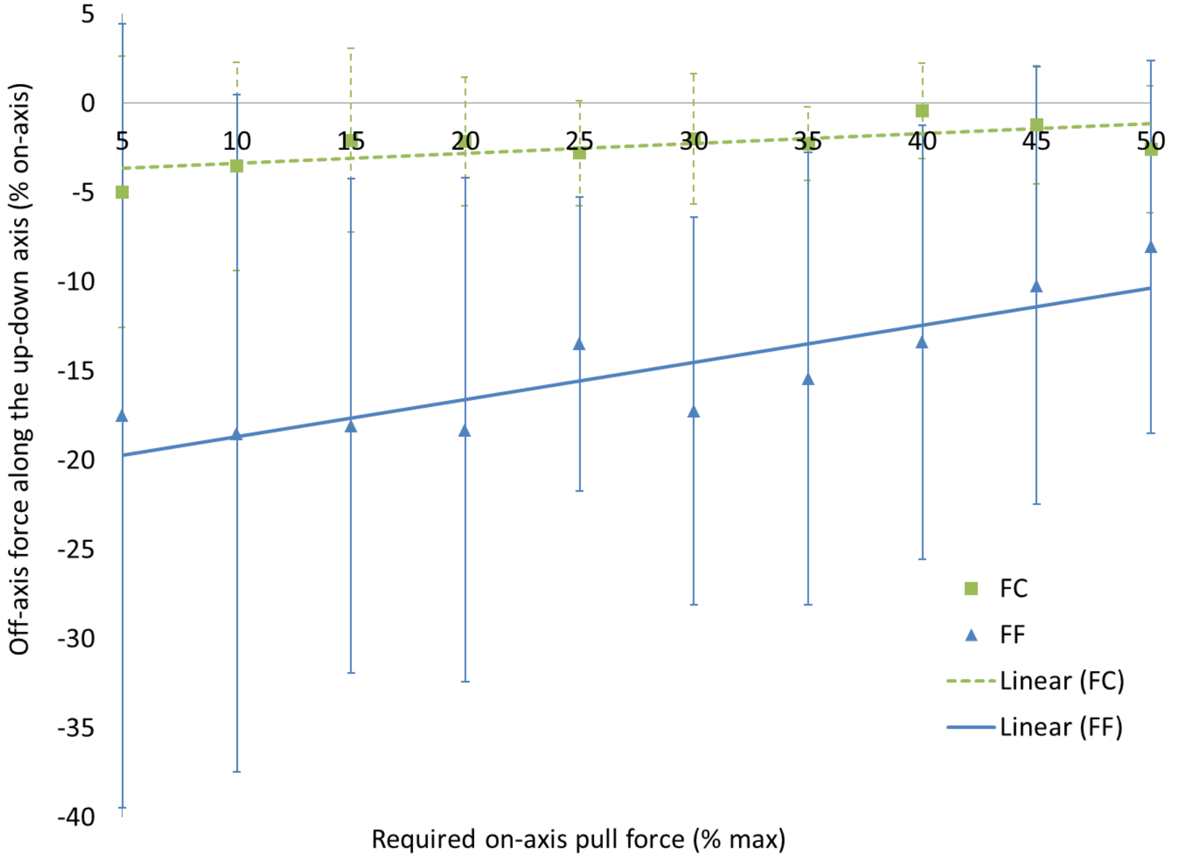

Figure 4.5 Off-axis force along the up-down axis during submaximal pull exertions for the free posture without (green, dotted line) and with (blue, solid line) off-axis force. There was more downward off-axis force when off-axis force was allowed compared to when it was not. The difference was consistent at 12.6% on-axis. For both conditions, the downward off-axis force deceased as required force level increased. Note: lines are for illustrative purposes.

There were condition and force main effects for off-axis force along the left-right axis (Table 4.6).

Table 4.6 Statistical significance for force along the left-right when comparing FC to FF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
FC to FF, left-right	Condition	$F_{1,17} = 12.66$	p = 0.0024*
	Force	$F_{9,153} = 3.28$	p = 0.0011*
	Condition*Force	$F_{9,149} = 1.19$	p = 0.3076

When off-axis force was allowed there was significantly more rightward off-axis force compared to when it was not allowed (Figure 4.6, Table B.2 in Appendix B). Further, for both conditions, as required submaximal force level increased, off-axis force to the right decreased and got closer to zero. The average off-axis force along the left-right axis for the without off-axis force condition was 3.0% on-axis (sd 4.2% on-axis n = 176) and for the with off-axis force condition was 7.7% on-axis (sd 9.0% on-axis n = 180), which was a difference of 4.7% on-axis. Further, Tukey post-hoc analysis revealed that rightward off-axis force was significantly higher at the required force level of 5% max compared to between 15% max and 50% max.

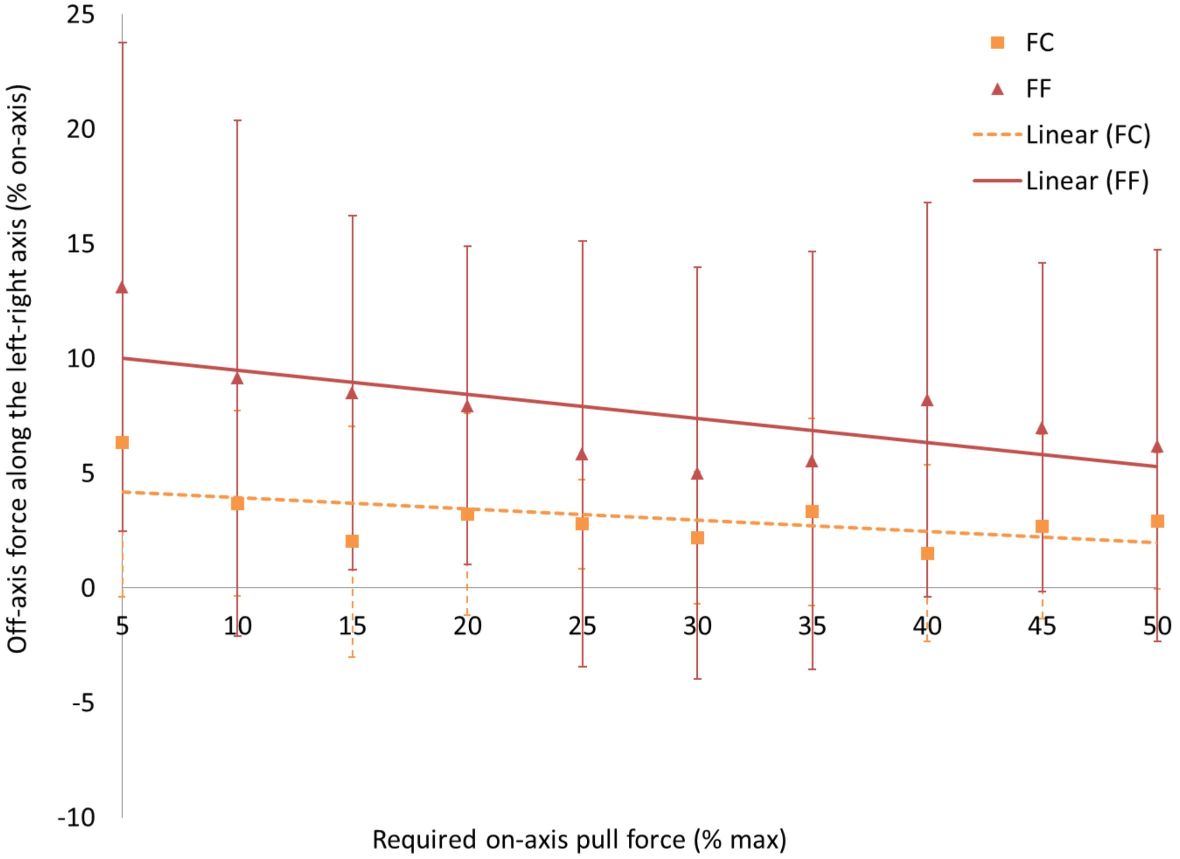

Figure 4.6 Off-axis force along the left-right axis during submaximal pull exertions for the free posture without (orange, dotted line) and with (red, solid line) off-axis force. There was more rightward off-axis force when off-axis force was allowed compared to when it was not. The difference was consistent at 4.7% on-axis. For both conditions, the rightward off-axis force deceased as required force level increased. Note: lines are for illustrative purposes.

4.3 Hypothesis 3

Evaluating hypothesis 3 required comparison of the constrained posture with off-axis force condition (CF) to the free posture with off-axis force condition (FF) across all required submaximal force levels for force along each of the off-axes (up-down and left-right).

For pushing exertions, there were condition and force main effects for off-axis force along the up-down axis (Table 4.7).

Table 4.7 Statistical significance for force along the up-down when comparing CF to FF across submaximal force levels during pushing (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CF to FF, up-down	Condition	$F_{1,17} = 22.69$	p = 0.0002*
	Force	$F_{9,153} = 4.39$	p = <0.0001*
	Condition*Force	$F_{9,151} = 0.62$	p = 0.7790

In the constrained posture, there was significantly more downward off-axis force compared to the free posture where there was a slight upward off-axis force (Figure 4.7, Table B.1 in Appendix B). Further, for both postural conditions, as the required submaximal force level increased off-axis force along the up-down axis increased. Specifically, for the constrained posture the downward off-axis force decreased (became more upwards) and for the free posture the upward off-axis force increased (Figure 4.7). The average off-axis force along the up-down axis for the constrained posture condition was -10.8% on-axis (sd 16.5% on-axis n = 180) and for the free posture condition was 2.1% on-axis (sd 17.6% on-axis n = 178), which is a difference of 12.9% on-axis. Further, Tukey post-hoc analysis revealed that downward off-axis force axis was significantly higher at the required force level of 5% max compared to between 25% max and 50% max.

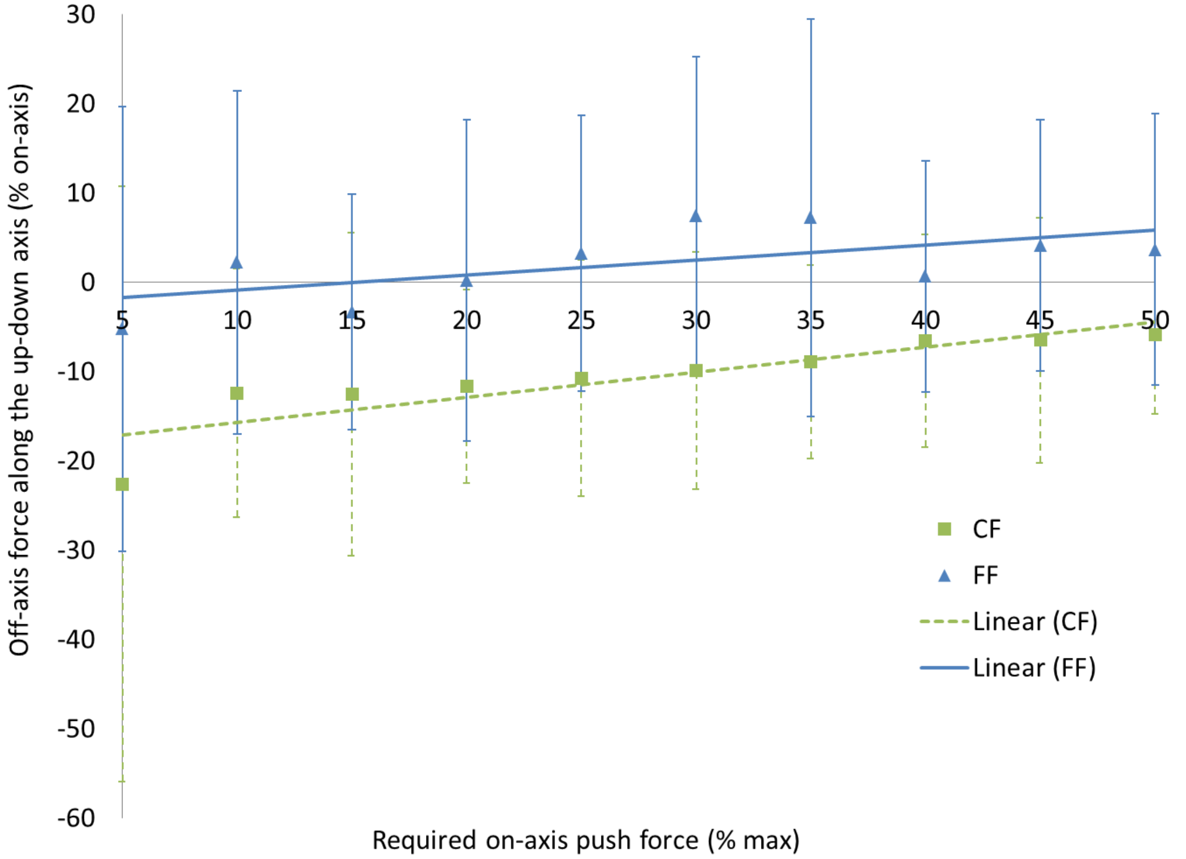

Figure 4.7 Off-axis force along the up-down axis during submaximal push exertions for the constrained (green, dotted line) and free (blue, solid line) posture with off-axis force. In the constrained posture the off-axis force was downward compared to in the free posture the off-axis force was slightly upward. This difference was consistent at 12.9% on-axis. For both conditions, the downward off-axis force deceased and the upward off-axis force increased as required force level increased. Note: lines are for illustrative purposes.

There were no significant main effects or interactions for off-axis force along the left-right axis (Table 4.8). Thus, there was no difference in off-axis force level along the left-right axis when posture was constrained.

Table 4.8 Statistical significance for force along the left-right when comparing CF to FF across submaximal force levels during pushing (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CF to FF, left-right	Condition	$F_{1,17} = 3.12$	p = 0.0952
	Force	$F_{9,153} = 1.57$	p = 0.1278
	Condition*Force	$F_{9,151} = 0.77$	p = 0.6409

For pulling exertions, there were condition and force main effects and a condition*force interaction for off-axis force along the up-down axis (Table 4.9).

Table 4.9 Statistical significance for force along the up-down when comparing CF to FF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CF to FF, up-down	Condition	$F_{1,17} = 26.37$	p = <0.0001*
	Force	$F_{9,153} = 4.66$	p = <0.0001*
	Condition*Force	$F_{9,153} = 2.62$	p = 0.0076*

In the constrained posture, there was less downward off-axis force compared to the free posture (Figure 4.8). This difference increased as required submaximal force level increased from 5% max to 50% max (Figure 4.8, Table B.2 in Appendix B). Particularly, Tukey post-hoc analysis showed that at the required submaximal force level of 5% max there was no significant difference in downwards off-axis force between the constrained and free postures (p = 0.1139).

Further, as the required submaximal force increased, downward off-axis force decreased and this change was more prevalent when posture was constrained compared to when it was free. Particularly, Tukey post-hoc analysis revealed that for the constrained posture there was significantly more downwards off-axis force at the required force level of 5% max compared to 10% max to 50% max (p = 0.0001, rest: <0.0001); and there was significantly less downwards off-axis force at 40% max compared to 10% max (p = 0.0011), 15% max (0.0261), 20% max (0.0031), and 35% max (p = 0.0367); 45% max compared to 10% max (p = 0.0040) and 20% max (0.0099); and 50% max compared to 10% max to 35% max (p = <0.0001, 0.0004, <0.0001, 0.0018, 0.0017, 0.0007). In fact in the constrained posture, downward off-axis force become slightly upward off-axis force at the required force level of 50% max where it was 1.3% on-axis (sd 7.8% on-axis n = 18). In comparison, Tukey post-hoc analysis for the free posture condition revealed significantly less downward off-axis force at 45% max compared to 5% max to 20% max (p = 0.0070, 0.0022, 0.0036, 0.0028) and 30% max (p = 0.0092), and at 50% max compared to 5% max to 40% max (p = 0.0005, 0.0001, 0.0002, 0.0002, 0.0433, 0.0007, 0.0063, 0.0472), where downwards off-axis force was -10.2% on-axis (sd 12.3% on-axis n = 18) and -8.1% on-axis (sd 10.4% on-axis n = 18), respectively. The overall change in downward off-axis force from the required force level of 5% max to 50% max for the constrained posture was 23.1% on-axis and for the free posture was 9.4% on-axis. This further shows the difference in the rates of change of off-axis force level between the two conditions.

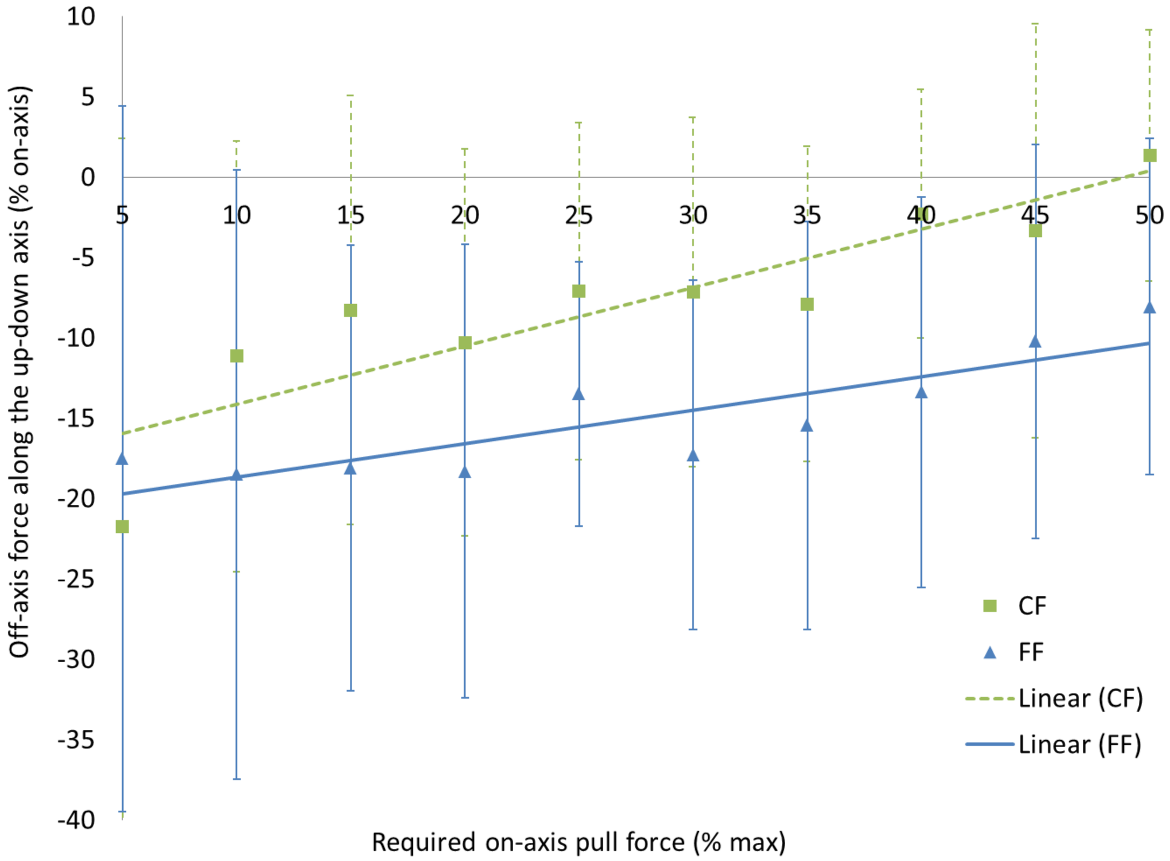

Figure 4.8 Off-axis force along the up-down axis during submaximal pull exertions for the constrained (green, dotted line) and free (blue, solid line) posture with off-axis force. In the constrained posture the off-axis force was more downward compared to in the free posture. This difference was not consistent and increased as required force level increased. For both conditions, the downward off-axis force deceased as required force level increased, but more so for the constrained posture compared to the free posture. Note: lines are for illustrative purposes.

There was a condition*force interaction for off-axis force along the left-right axis (Table 4.10).

Table 4.10 Statistical significance for force along the left-right when comparing CF to FF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CF to FF, left-right	Condition	$F_{1,17} = 0.24$	p = 0.6293
	Force	$F_{9,153} = 0.53$	p = 0.8538
	Condition*Force	$F_{9,153} = 3.51$	p = 0.0006*

In the constrained posture, off-axis force to the right increased whereas in the free posture it decreased as required submaximal force level increased from 5% max to 50% max (Figure 4.9, Table B.2 in Appendix B). Specifically, Tukey post-hoc analysis showed that in the constrained posture, off-axis force to the right was significantly less at the required force level of 5% max compared to 20% max (p = 0.0133) and 35% max to 50% max (p = 0.0105, 0.0357, 0.0005, 0.0039); and significantly more at 45%

max compared to 10% max (p = 0.0090), 15% max (p = 0.0401) and 25% max (p = 0.0227), and at 50% max compared to 10% max (p = 0.0456). Conversely, Tukey post-hoc analysis showed in the free posture rightward off-axis force was significantly more at the required force level of 5% max compared to 20% max to 50% max (p = 0.0285, 0.0022, 0.0007, 0.0015, 0.0371, 0.0096, 0.0035). These analyses further show the increasing trend of the constrained posture condition and the downward trend of the free posture condition as required submaximal force was increased. Further, the overall change in rightward off-axis force from the required force level of 5% max to 50% max for the constrained posture was 6.8% on-axis and for the free posture was 6.9% on-axis. This indicates that even though in the opposite direction, the rate of change of off-axis force level between the two conditions was similar.

Finally, Tukey post-hoc analysis revealed that rightward off-axis force was significantly lower in the constrained posture compared to the free posture condition at the required force level of 5% max (p = <0.0001). Rightward off-axis force at 5% max for the constrained posture was 2.5% on-axis (sd 15.6% on-axis n = 18) and for the free posture was 13.1% on-axis (sd 10.6% on-axis n = 18), which was a difference of 10.6% on-axis. This was the only required force level where off-axis force to the right was significantly different between postural conditions and indicates the only difference between the two conditions was in the direction of the rate of change of the rightward off-axis force.

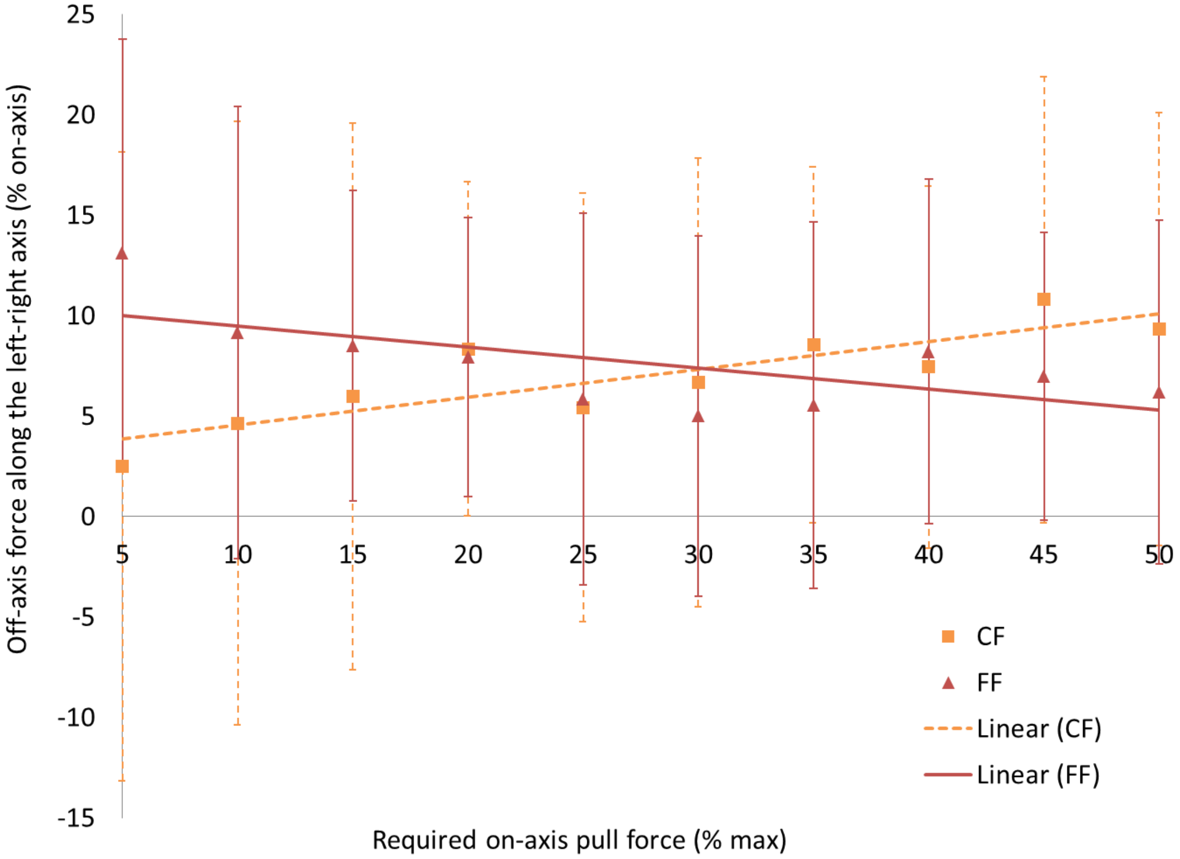

Figure 4.9 Off-axis force along the left-right axis during submaximal pull exertions for the constrained (orange, dotted line) and free (red, solid line) posture with off-axis force. In the constrained posture off-axis force to the right increased whereas in the free posture it decreased. These rates of change were opposite in direction by similar in magnitude. Note: lines are for illustrative purposes.

4.4 Hypothesis 4

First, evaluating hypothesis 4 required comparison of the constrained posture with off-axis force condition (CF) to the constrained posture without off-axis force condition (CC) across all required submaximal force levels for force along the off-axes (up-down and left-right).

For pushing exertions, there were condition and force main effects for off-axis force along the up-down axis (Table 4.11).

Table 4.11 Statistical significance for force along the up-down when comparing CC to CF across submaximal force levels during pushing (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, up-down	Condition	$F_{1,17} = 13.44$	p = 0.0019*
	Force	$F_{9,153} = 3.48$	p = 0.0006*
	Condition*Force	$F_{9,142} = 1.04$	p = 0.4147

In the constrained posture when off-axis forces were allowed there was significantly more downward off-axis force compared to when they were not allowed (Figure 4.10, Table B.1 in Appendix B). Further, for both conditions, as the required submaximal force level increased, the downward off-axis force decreased and got closer to zero. Specifically, Tukey post-hoc analysis revealed that downward off-axis force was significantly lower at the required force level of 5% max compared to between 20% max and 50% max. The average off-axis force along the up-down axis for the constrained posture without off-axis force condition was -1.8% on-axis (sd 5.4% on-axis n = 169) and for the constrained posture with off-axis force condition was -10.8% on-axis (sd 16.5% on-axis n = 180), which was a difference of 9.0% on-axis.

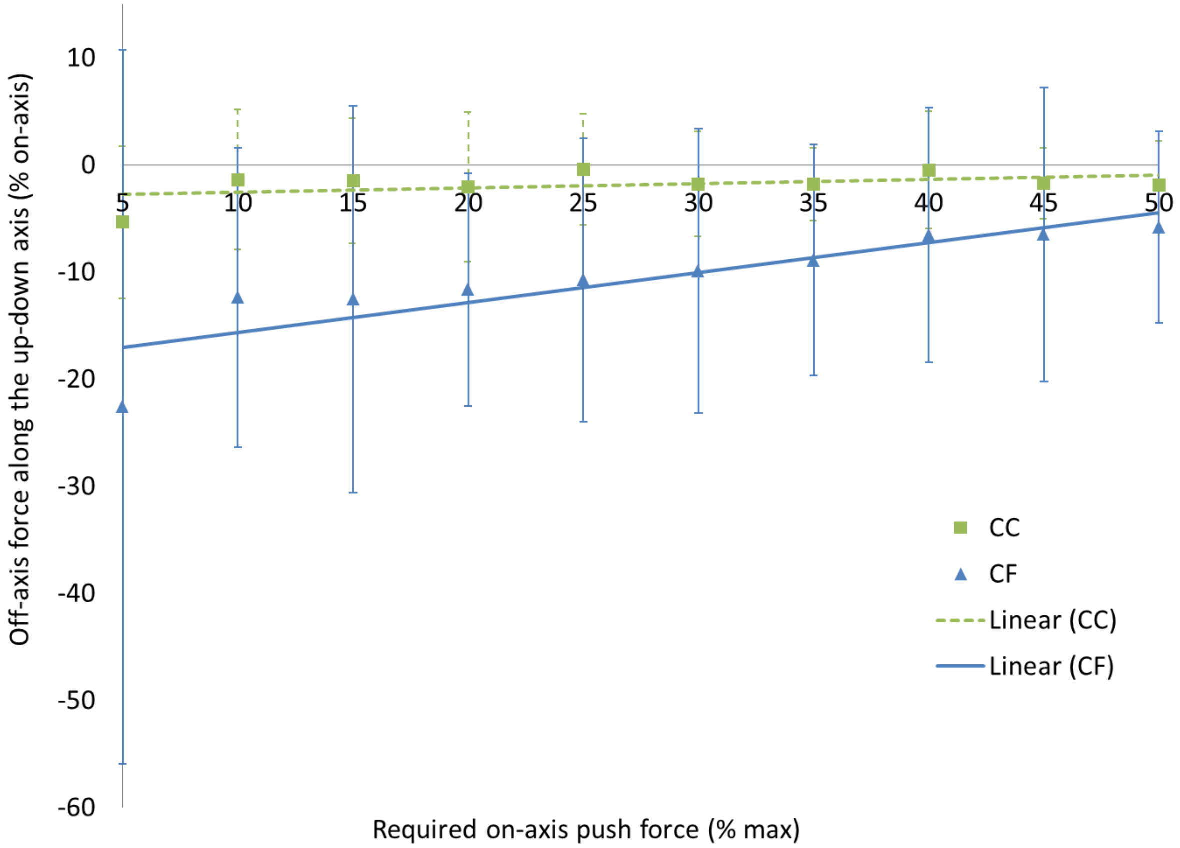

Figure 4.10 Off-axis force along the up-down axis during submaximal push exertions for the constrained posture without (green, dotted line) and with (blue, solid line) off-axis force. In the constrained posture, when off-axis force was allowed there was more downward off-axis force compared to when it was not allowed. This difference was consistent at 9.0% on-axis. For both conditions, the downward off-axis force deceased as required force level increased. Note: lines are for illustrative purposes.

There were no significant main effects or interaction for off-axis force along the left-right axis (Table 4.12). Thus, there was no difference in off-axis force level along the left-right axis for both postural conditions when off-axis force was allowed or not allowed.

Table 4.12 Statistical significance for force along the left-right when comparing CC to CF across submaximal force levels during pushing (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, left-right	Condition	$F_{1,17} = 1.65$	p = 0.2164
	Force	$F_{9,153} = 1.02$	p = 0.4277
	Condition*Force	$F_{9,142} = 1.56$	p = 0.1342

For pulling exertions, there were condition and force main effects and a condition*force interaction for off-axis force along the up-down axis (Table 4.13).

Table 4.13 Statistical significance for force along the up-down when comparing CC to CF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, up-down	Condition	$F_{1,17} = 23.44$	p = 0.0002*
	Force	$F_{9,153} = 4.00$	p = 0.0001*
	Condition*Force	$F_{9,147} = 5.87$	p = <0.0001*

In the constrained posture, when off-axis force was allowed there was significantly more downward off-axis force compared to when it was not allowed (Figure 4.11, Table B.2 in Appendix B). This difference significantly decreased as the required submaximal force level increased. Specifically, Tukey post-hoc analysis showed that for the constrained posture condition with off-axis force, downward off-axis force at the required force level of 5% max was significantly greater than at 10% max to 50% max (all p = <0.0001); whereas downward off-axis force was significantly less at 40% max compared to 10% max to 20% max (p = 0.0005, 0.0176, 0.0016) and 35% (p = 0.0257); 45% max compared to 10% max to 20% max (p = 0.0021, 0.0498, 0.0059); and 50% max compared to 10% max to 35% max (p = <0.0001, 0.0002, <0.0001, 0.0009, 0.0008, 0.0003). This indicates that for the constrained posture condition with off-axis force, there was a significant decrease in downward off-axis force as required force level increased. In fact, the overall change in downward off-axis force from the required force level of 5% max to 50% max was 23.1% on-axis when off-axis force was allowed. In comparison, when off-axis force was not allowed, there was a very small change in off-axis force level from 5% max to 50% of 1.8% on-axis, which indicates that the rate of change was nearly zero for this condition.

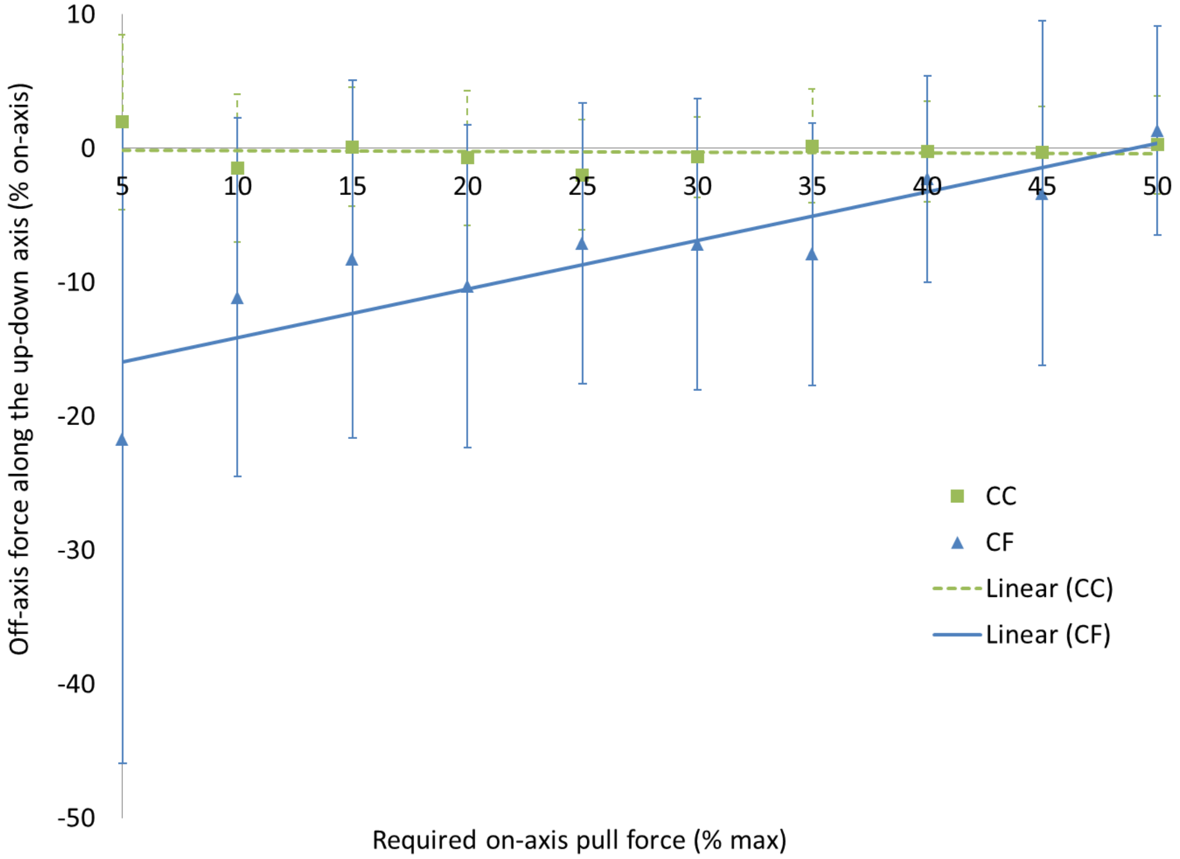

Figure 4.11 Off-axis force along the up-down axis during submaximal pull exertions for the constrained posture without (green, dotted line) and with (blue, solid line) off-axis force. In the constrained posture, when off-axis force was allowed there was more downward off-axis force compared to when it was not allowed. This difference significantly decreased as required submaximal force level increased because there was significant decrease in downward off-axis force when off-axis force was allowed. In comparison, when off-axis force was not allowed, the trend was flat. Note: lines are for illustrative purposes.

There was a condition main effect for off-axis force along the left-right axis (Table 4.14).

Table 4.14 Statistical significance for force along the left-right when comparing CC to CF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, left-right	Condition	$F_{1,17} = 7.33$	p = 0.0149*
	Force	$F_{9,153} = 1.31$	p = 0.2345
	Condition*Force	$F_{9,147} = 0.74$	p = 0.6676

In the constrained posture, when off-axis force was allowed there was significantly more off-axis force to the right compared to when it was not allowed (Figure 4.12, Table B.2 in Appendix B). This difference was consistent across all required submaximal force levels. The average off-axis force along the left-right axis for the constrained posture without off-axis force condition was 2.5% on-axis (sd 5.2% on-axis n = 174) and for the constrained posture with off-axis force condition was 7.0% on-axis (sd 11.6% on-axis n = 180), which is a difference of 4.5% on-axis.

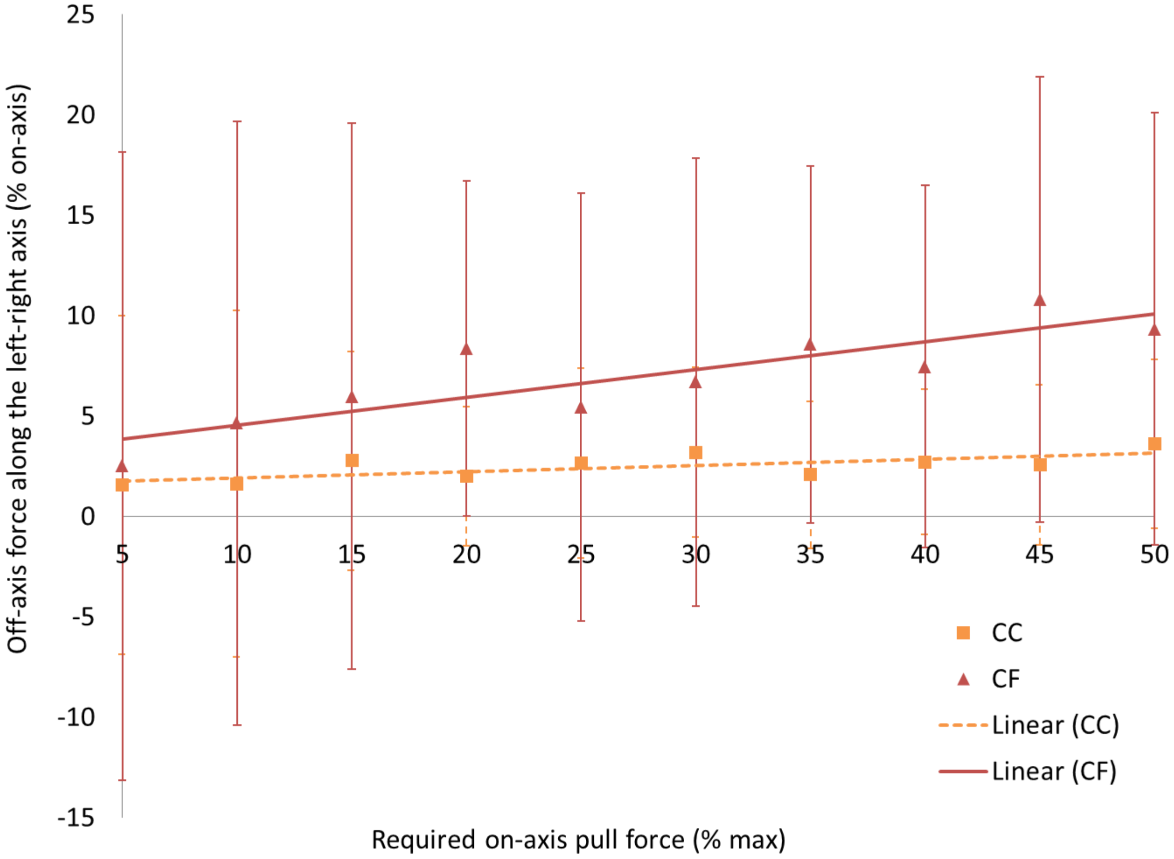

Figure 4.12 Off-axis force along the left-right axis during submaximal pull exertions for the constrained posture without (orange, dotted line) and with (red, solid line) off-axis force. In the constrained posture, when off-axis force was allowed there was more rightward off-axis force compared to when it was not allowed. This difference was consistent at 4.5% on-axis. Note: lines are for illustrative purposes.

Second, evaluating hypothesis 4 required comparison of the constrained posture without off-axis force condition (CC) to the constrained posture with off-axis force condition (CF) across all required submaximal force levels for moment about each of the anatomically relevant axes for the right upper extremity.

For pushing, there was a force main effect for the moment about the shoulder flexion-extension (flex-extn), shoulder abduction-adduction (ab-ad), shoulder internal-external rotation (int-extr), elbow supination-pronation (sup-pro), wrist flexion-extension (flex-extn), and wrist radial-ulnar deviation (rad-uln) axes (Table 4.15).

Table 4.15 Significant main effect of force for shoulder, elbow and wrist moments when comparing CC to CF across submaximal force levels during pushing (green and * indicates statistical significance)

Condition, Axis	Factor	F	p
CC to CF, shoulder flex-extn	Force	$F_{9,153} = 18.43$	p = <0.0001*
CC to CF, shoulder ab-ad	Force	$F_{9,153} = 196.19$	p = <0.0001*
CC to CF, shoulder int-extr	Force	$F_{9,144} = 142.33$	p = <0.0001*
CC to CF, elbow sup-pro	Force	$F_{9,153} = 74.72$	p = <0.0001*
CC to CF, wrist flex-extn	Force	$F_{9,153} = 28.04$	p = <0.0001*
CC to CF, wrist rad-uln	Force	$F_{9,153} = 10.63$	p = <0.0001*

For the previously mentioned moments, as the required submaximal force increased, the moment also increased. For these moments, there was no difference whether off-axis force was allowed or not for the constrained posture conditions. This means, off-axis force allowance did not change these moments during pushing exertions.

There were condition and force main effects for the moment about the elbow flex-extn axis (Table 4.16).

Table 4.16 Statistical significance for moment about the elbow flex-extn axis when comparing CC to CF across submaximal force levels during pushing (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, elbow flex-extn	Condition	$F_{1,17} = 20.91$	p = 0.0003*
	Force	$F_{9,153} = 66.42$	p = <0.0001*
	Condition*Force	$F_{9,142} = 1.71$	p = 0.0921

In the constrained posture, when off-axis force was allowed elbow extension moment was greater compared to when it was not allowed (Figure 4.13, Tables B.3 and B.4 in Appendix B). This difference was consistent across all required submaximal force levels. Further, as required submaximal force increased, elbow extension moment also increased regardless of whether off-axis force was allowed or not. Elbow extension moment for the constrained posture without off-axis force condition was -3.5% cap (sd 2.6% cap n = 169) and for the constrained posture with off-axis force condition was -4.5% cap (sd 3.2% cap n = 180), which was a difference of 1.0% cap.

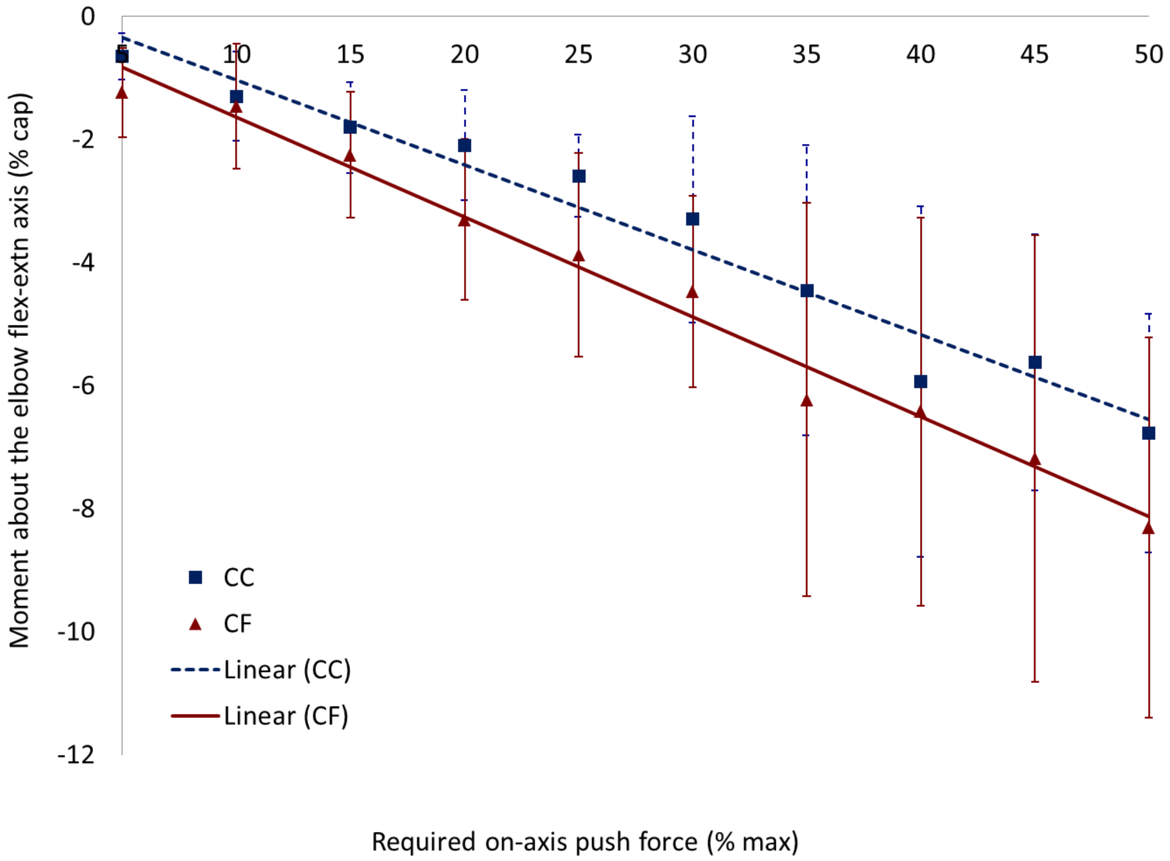

Figure 4.13 Moment about the elbow flex-extn axis during submaximal push exertions for the constrained posture without (navy, dotted line) and with (burgundy, solid line) off-axis. Elbow extension moment was greater by 1.0% cap when off-axis force was allowed compared to not allowed. This difference was consistent across all required force levels. Further, as required submaximal force level increased, elbow extension moment increased for both conditions. Note: lines are for illustrative purposes.

For pulling, there was a force main effect for the moment about the shoulder internal-external rotation (int-extr), elbow flexion-extension (flex-extn) and wrist radial-ulnar deviation (rad-uln) axes (Table 4.17).

Table 4.17 Significant main effect of force for shoulder, elbow and wrist moments when comparing CC to CF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factor	F	p
CC to CF, shoulder int-extr	Force	$F_{9,144} = 162.62$	p = <0.0001*
CC to CF, elbow flex-extn	Force	$F_{9,153} = 40.36$	p = <0.0001*
CC to CF, wrist rad-uln	Force	$F_{9,153} = 11.51$	p = <0.0001*

For the previously mentioned moments, as the required submaximal force increased, the moment also increased (Tables B.5 and B.6 in Appendix B). For these moments, there was no difference whether off-axis force was allowed or not for the constrained posture conditions. This means, off-axis force allowance did not change these moments during pulling exertions.

There were condition and force main effects for the moment about the shoulder flex-extn axis (Table 4.18).

Table 4.18 Statistical significance for moment about the shoulder flex-extn axis when comparing CC to CF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, shoulder flex-extn	Condition	$F_{1,17} = 8.64$	p = 0.0092*
	Force	$F_{9,153} = 19.08$	p = <0.0001*
	Condition*Force	$F_{9,147} = 1.78$	p = 0.0759

In the constrained posture, when off-axis force was allowed shoulder extension moment was less compared to when it was not allowed (Figure 4.14, Tables B.5 and B.6 in Appendix B). This difference was consistent across all required submaximal force levels. Further, as required submaximal force increased, shoulder extension moment also increased regardless of whether off-axis force was allowed or not. Shoulder extension moment for the constrained posture without off-axis force condition was -10.0% cap (sd 7.8% cap n = 174) and for the constrained posture with off-axis force condition was -7.6% cap (sd 9.1% cap n = 180), which was a difference of 2.4% cap.

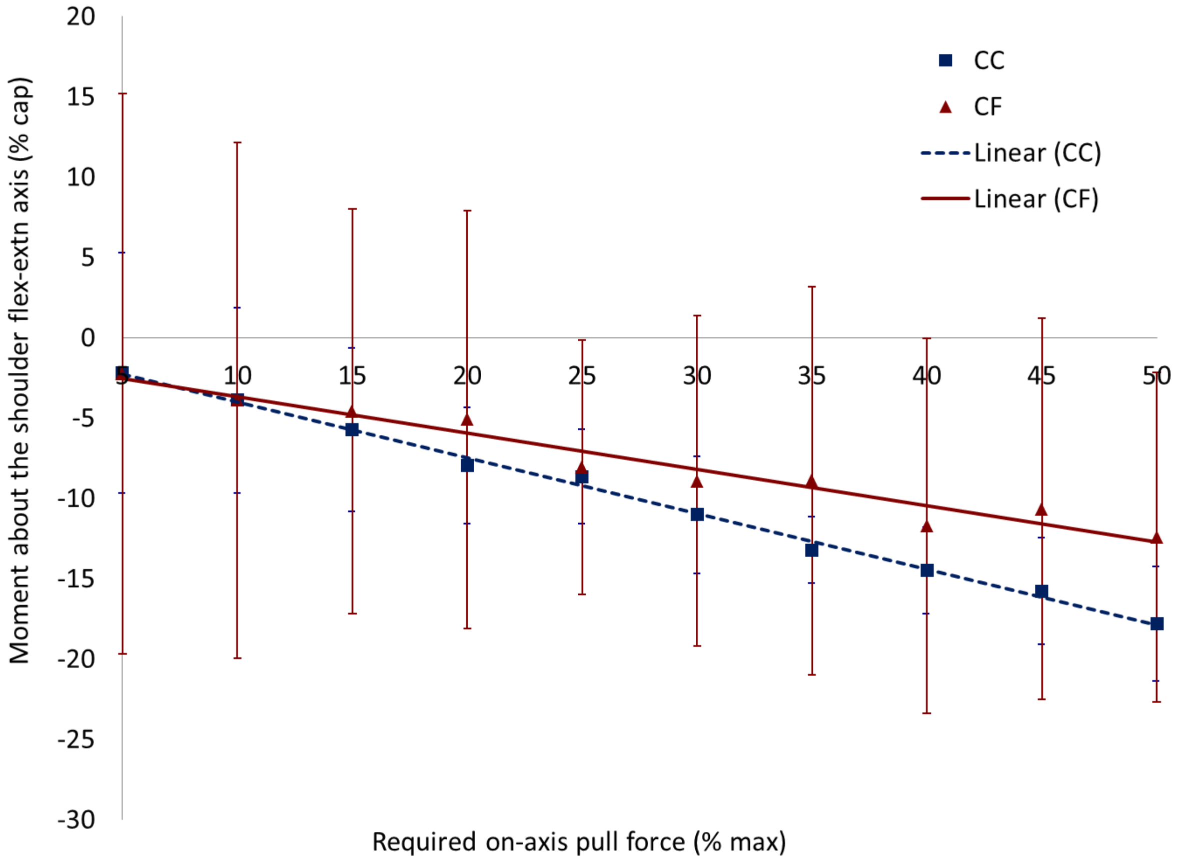

Figure 4.14 Moment about the shoulder flex-extn axis during submaximal pull exertions for the constrained posture without (navy, dotted line) and with (burgundy, solid line) off-axis force. Shoulder extension moment was less by 2.4% cap when off-axis force was allowed compared to not allowed. This difference was consistent across all required force levels. Further, as required submaximal force level increased, shoulder extension moment increased for both conditions. Note: lines are for illustrative purposes.

There were condition and force main effects for the moment about the shoulder ab-ad axis (Table 4.19).

Table 4.19 Statistical significance for moment about the shoulder ab-ad axis when comparing CC to CF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, shoulder ab-ad	Condition	$F_{1,17} = 6.02$	p = 0.0252*
	Force	$F_{9,153} = 116.59$	p = <0.0001*
	Condition*Force	$F_{9,147} = 0.89$	p = 0.5368

In the constrained posture, when off-axis force was allowed shoulder adduction moment was greater compared to when it was not allowed (Figure 4.15, Tables B.5 and B.6 in Appendix B). This difference was consistent across all required submaximal force levels. Further, as required submaximal force increased, shoulder adduction moment also increased regardless of whether off-axis force was allowed or not. Shoulder adduction moment for the constrained posture without off-axis force condition was -

13.5% cap (sd 12.8% cap n = 174) and for the constrained posture with off-axis force condition was -14.5% cap (sd 13.3% cap n = 180), which was a difference of 1.0% cap.

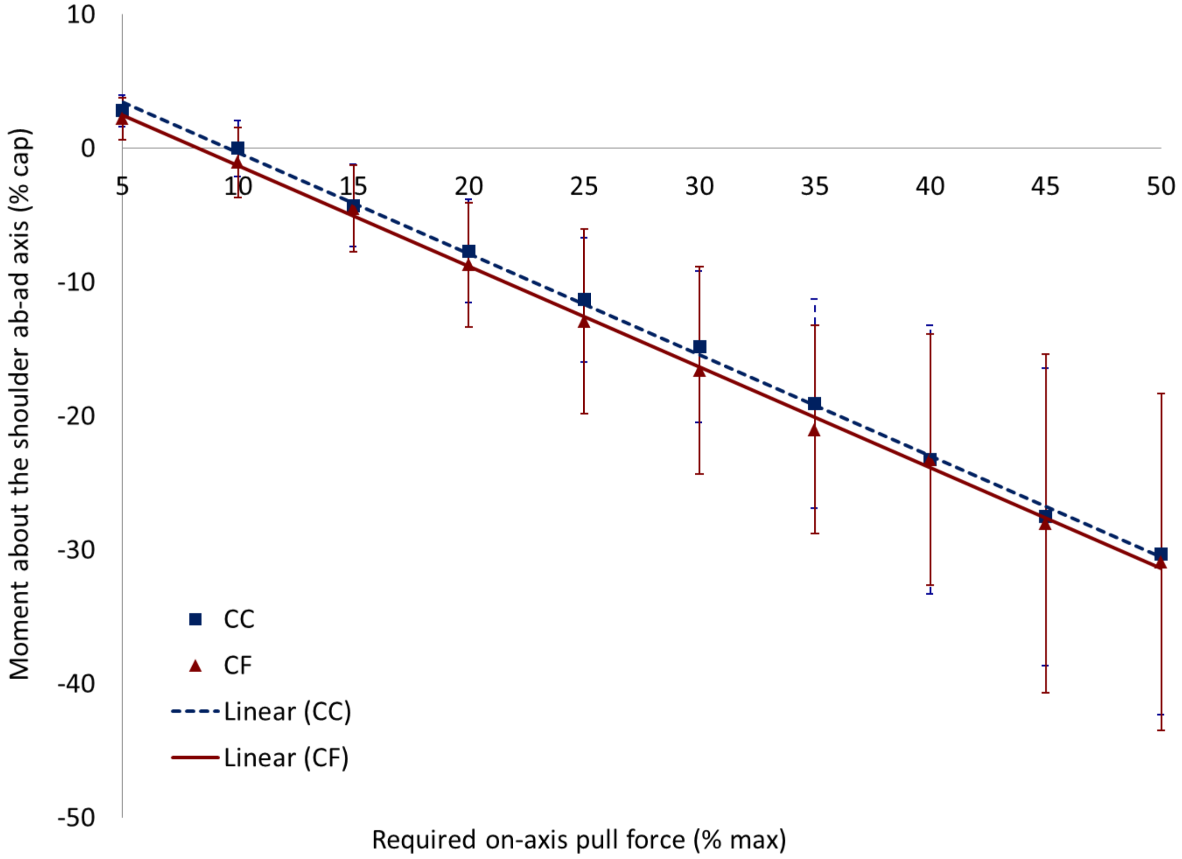

Figure 4.15 Moment about the shoulder abduction-adduction axis during submaximal pull exertions for the constrained posture without (navy, dotted line) and with (burgundy, solid line) off-axis. Shoulder adduction moment was greater by 1.0% cap when off-axis force was allowed compared to not allowed. This difference was consistent across all required force levels. Further, as required submaximal force level increased, shoulder adduction moment increased for both conditions. Note: lines are for illustrative purposes.

There was a force main effect and condition*force interaction for the moment about the elbow supination-pronation (sup-pro) axis (Table 4.20).

Table 4.20 Statistical significance for moment about the elbow sup-pro axis when comparing CC to CF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, elbow sup-pro	Condition	$F_{1,17} = 2.85$	p = 0.1098
	Force	$F_{9,153} = 182.27$	p = <0.0001*
	Condition*Force	$F_{9,147} = 2.01$	p = 0.0415*

In the constrained posture, as required submaximal force increased, elbow supination moment also increased at a significantly lower rate of change when off-axis force was allowed compared to when it was not (Figure 4.16, Tables B.5 and B.6 in Appendix B). The difference in elbow supination moment between the required force level of 5% max and 50% max was -128.5% cap when off-axis force was not allowed and -114.6% cap when off-axis force was allowed. The difference in elbow supination moment appeared to increase as required submaximal force increased, especially at the required force levels of 45% max and 50% max where elbow supination was less when off-axis force was allowed compared to not allowed.

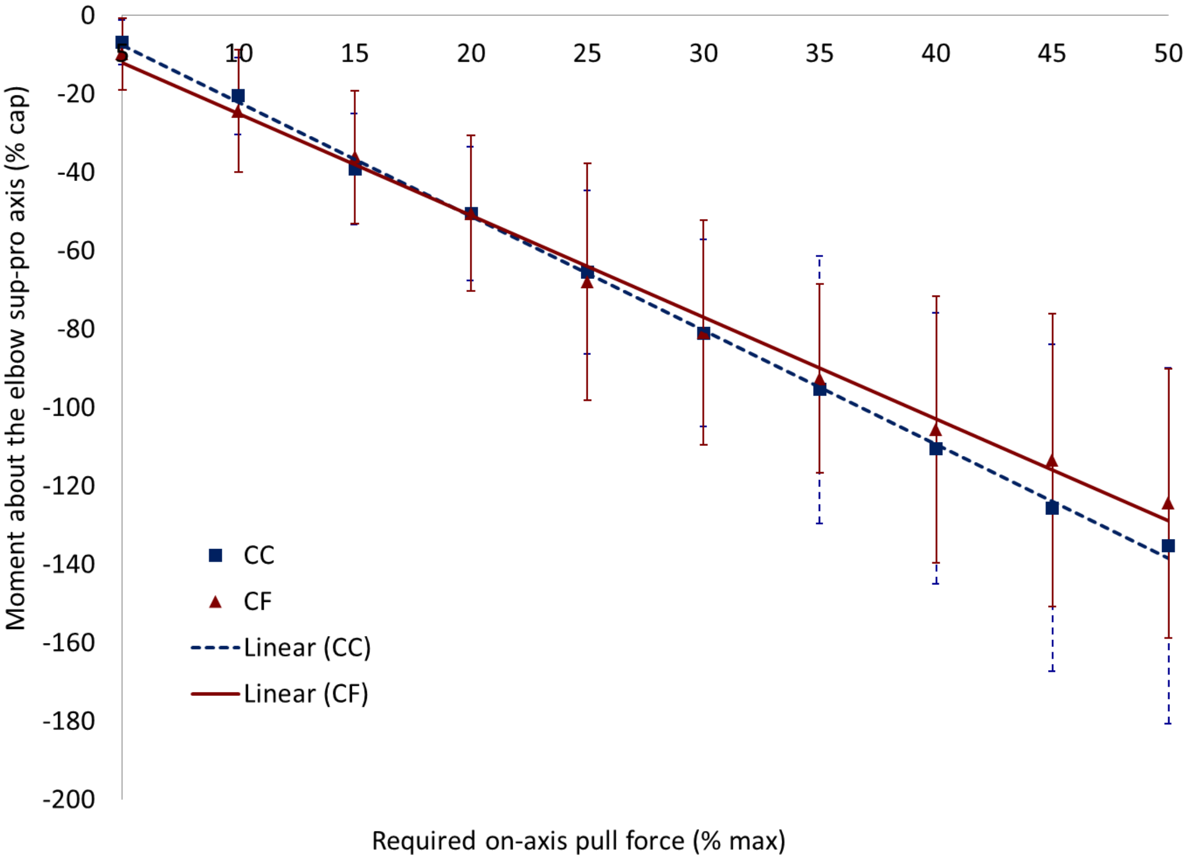

Figure 4.16 Moment about the elbow sup-pro axis during submaximal push exertions for the constrained posture without (navy, dotted line) and with (burgundy, solid line) off-axis force. As required submaximal force level increased, elbow supination moment increased at a significantly lower rate of change when off-axis force was allowed compared to not allowed. Note: lines are for illustrative purposes.

There were condition and force main effects, and a condition*force interaction for the moment about the wrist flexion-extension (flex-extn) axis (Table 4.21).

Table 4.21 Statistical significance for moment about the wrist flex-extn axis when comparing CC to CF across submaximal force levels during pulling (green and * indicates statistical significance)

Condition, Axis	Factors	F	p
CC to CF, wrist flex-extn	Condition	$F_{1,17} = 5.22$	p = 0.0355*
	Force	$F_{9,153} = 13.09$	p = <0.0001*
	Condition*Force	$F_{9,147} = 2.14$	p = 0.0296*

In the constrained posture, when off-axis force was allowed wrist flexion moment was less compared to when it was not allowed (Figure 4.17, Tables B.5 and B.6 in Appendix B). This difference significantly increased as required submaximal force level increased, as the rate of change of wrist flexion moment was significantly lower when off-axis force was allowed compared to not allowed. Specifically, the difference in wrist flexion moment between the required force level of 5% max and 50% max was 68.9% cap when off-axis force was not allowed and 40.3% cap when off-axis force was allowed. Further, for both conditions, as submaximal force level increased the wrist flexion moment significantly increased.

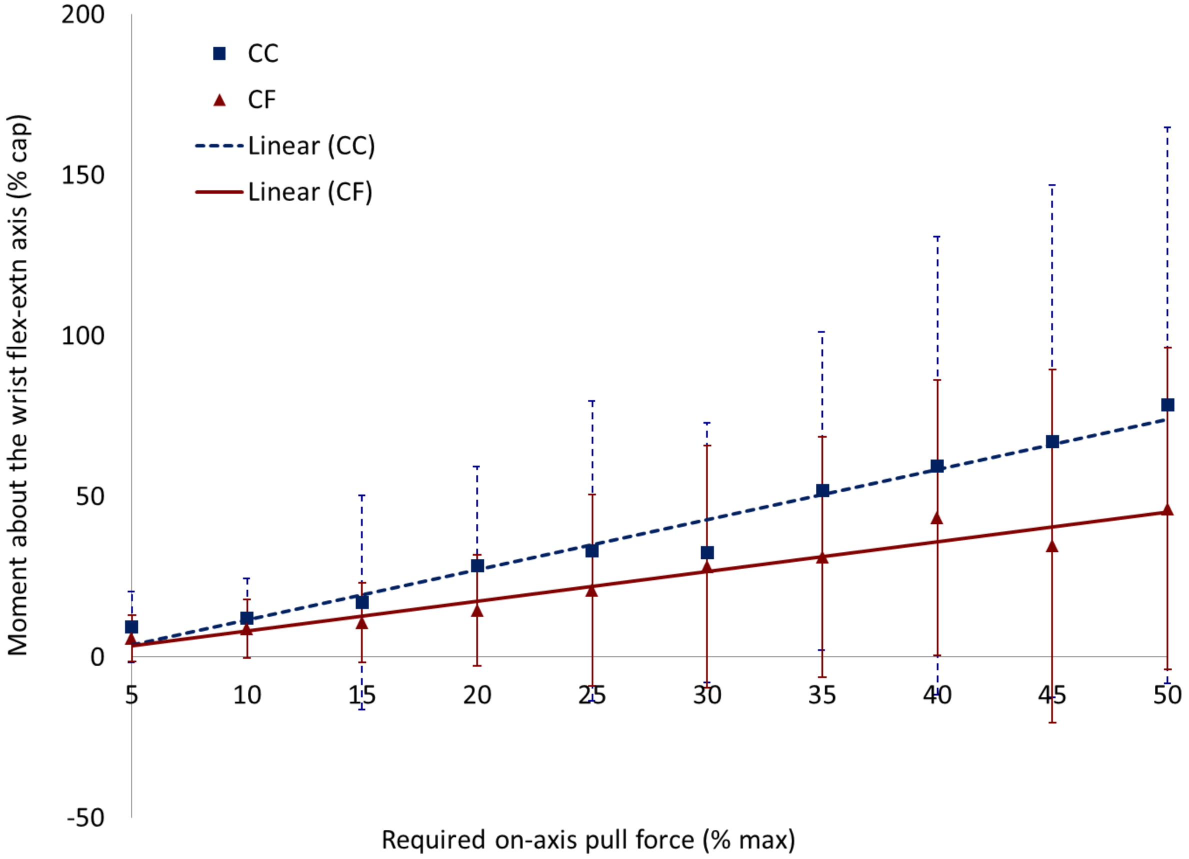

Figure 4.17 Moment about the elbow sup-pro axis during submaximal push exertions for the constrained posture without (navy, dotted line) and with (burgundy, solid line) off-axis force. Wrist flexion moment was significantly less when off-axis force was allowed compared to not. This difference significantly increased as required submaximal force increased. Further, as required submaximal force level increased, wrist flexion moment increased at a significantly lower rate of change when off-axis force was allowed compared to not. Note: lines are for illustrative purposes.

4.5 Validation of Experimental Conditions

The following section evaluated each of the monitored condition requirements. The implications of these results were discussed in the limitations section of the discussion.

4.5.1 Required Force Level

For both pushing and pulling, participants generally met the required force levels with low standard deviation (less than 2.0% of the maximum force achievable in the free condition (% max)). Participants were able to meet the required force level with more accuracy during pushing compared to pulling. For pushing exertions, force levels were slightly over the required force level for 5% max, approximately at the proper level for 10% max to 35% max, and slightly under the required level for 40% max to 50% max (Table 4.22). The constrained posture condition without off-axis force (CC) was the worst condition for participants meeting the required force levels, with force levels lower than required for half of the exertions. The free posture with off-axis force condition (FF) was the best condition for participants meeting the required force levels.

Table 4.22 Matching required on-axis push force level for all conditions (peach coloured cells were either over or under the required force level)

	Condition			
Required Force Level (% max)	FF	FC	CF	CC
	mean (sd)	mean (sd)	mean (sd)	mean (sd)
5	6.3 (0.9)	6.1 (0.8)	6.2 (1.1)	5.8 (0.9)
10	10.8 (1.2)	11.0 (1.3)	10.4 (0.9)	10.4 (1.2)
15	15.5 (1.2)	15.2 (1.9)	15.4 (1.0)	14.5 (1.5)
20	20.5 (1.4)	20.0 (1.8)	20.0 (1.3)	19.6 (1.8)
25	25.0 (1.2)	24.2 (1.9)	24.6 (1.3)	24.4 (1.4)
30	29.4 (1.5)	29.4 (2.0)	29.3 (1.4)	28.5 (1.7)
35	34.9 (1.8)	34.5 (1.4)	34.5 (1.4)	33.2 (1.7)
40	39.5 (1.2)	38.9 (2.2)	38.9 (1.3)	38.2 (1.9)
45	43.7 (1.3)	43.0 (1.8)	43.6 (1.5)	43.0 (1.8)
50	49.1 (1.2)	47.9 (1.5)	47.9 (1.6)	47.7 (1.9)

For pulling exertions, force levels were approximately at the proper level for 5% max to 15% max and slightly under the required level for 20% max to 50% max (Table 4.23). The free posture condition without off-axis forces (FC), the constrained posture condition with off-axis forces (CF) and the constrained posture condition without off-axis force (CC) were the worse conditions for participants meeting the required force levels, with the majority of the force levels being lower than the required force level. The free posture with off-axis force condition (FF) was the best condition for participants meeting the required force levels, but force levels were still lower than required for half of the exertions.

Table 4.23 Matching required on-axis pull force level for all conditions (peach coloured cells were either over or under the required force level)

	Condition			
Required Force Level (% max)	FF	FC	CF	CC
	mean (sd)	mean (sd)	mean (sd)	mean (sd)
5	5.5 (1.1)	5.7 (1.5)	5.7 (1.4)	5.4 (1.1)
10	10.0 (1.2)	9.6 (1.6)	10.0 (1.1)	9.5 (1.5)
15	14.9 (1.2)	14.4 (1.5)	14.3 (1.3)	15.1 (1.5)
20	19.1 (1.3)	18.5 (1.3)	18.9 (1.4)	18.8 (1.7)
25	24.0 (1.5)	23.3 (1.1)	23.6 (1.2)	23.5 (1.5)
30	28.6 (1.1)	27.9 (1.3)	28.4 (1.4)	27.9 (1.4)
35	32.8 (0.9)	33.0 (2.4)	33.0 (0.9)	32.7 (1.6)
40	37.8 (1.1)	37.5 (1.6)	37.3 (1.2)	36.8 (1.2)
45	42.5 (1.2)	42.1 (1.4)	42.7 (1.3)	41.7 (1.5)
50	47.1 (1.1)	46.6 (1.4)	46.8 (1.2)	46.2 (1.9)

4.5.2 Constrained Posture Variation

During experimentation, participants were instructed for the constrained posture conditions to maintain a posture such that their right upper extremity was in the 60-degree shoulder plane of elevation (where 0 degrees is abduction and 90 degrees is flexion), at 30 degrees of upper arm elevation (measured from the torso), at 100 degrees elbow included angle (in flexion), and 140 degrees wrist included angle (in extension).

For pushing exertions, the average angles for the plane of elevation was approximately 59 degrees, the arm elevation was approximately 35 degrees, the elbow included angle was approximately 85 degrees, and the wrist included angle was approximately 161 degrees (Table 4.24). The lowest standard deviation was for the arm elevation angle and was approximately 4 degrees. The elbow included angle had the next lowest standard deviation followed by the plane of elevation at approximately 7 and 9 degrees, consecutively. The largest standard deviation was for the wrist included angle at approximately 12 degrees.

Table 4.24 Postural variation during push exertions for constrained posture conditions

Angle (Degrees)		Condition			
		Max CF	Max CC	Submax CF	Submax CC
POE	mean (sd)	60.6 (9.9)	59.5 (8.8)	58.6 (7.9)	57.8 (8.2)
ELV	mean (sd)	-35.4 (4.4)	-35.2 (3.3)	-34.7 (4.0)	-34.6 (4.0)
ELB	mean (sd)	83.5 (7.6)	84.2 (7.3)	85.5 (6.5)	85.9 (6.2)
WR	mean (sd)	161.0 (12.6)	160.6 (10.9)	161.6 (11.6)	161.2 (12.3)

For pulling exertions, the average angles for the plane of elevation was approximately 58 degrees, the arm elevation was approximately 32 degrees, the elbow included angle was approximately 87 degrees, and the wrist included angle was approximately 161 degrees (Table 4.25). The lowest standard deviation was for the arm elevation angle and was approximately 4 degrees. The elbow-included angle had the next lowest standard deviation followed by the plane of elevation at approximately 7 and 10 degrees, consecutively. The largest standard deviation was for the wrist-included angle at approximately 13 degrees.

Table 4.25 Postural variation during pull exertions for constrained posture conditions

Angle (Degrees)		Condition			
		Max CF	Max CC	Submax CF	Submax CC
POE	mean (sd)	59.7 (10.9)	59.8 (10.5)	57.9 (8.6)	57.1 (8.8)
ELV	mean (sd)	-31.1 (4.1)	-31.6 (4.0)	-32.2 (4.0)	-31.9 (3.8)
ELB	mean (sd)	86.1 (7.8)	87.4 (7.8)	87.4 (6.4)	88.0 (6.3)
WR	mean (sd)	162.2 (15.3)	158.7 (14.9)	159.9 (11.0)	161.3 (12.4)

4.5.3 Off-Axis Force and Moment Variation

Off-axis forces were kept between +/- 10% of the on-axis force level (% on-axis) during submaximal trials as best as possible during experimentation. Once processed it was noted that many data points would have to be removed in order to maintain this off-axis force allowance for all conditions without off-axis forces. Statistical analysis was run on three levels of off-axis force allowance to see how these levels affected the results for both push and pull exertions (Table 4.26, Table 4.27). The three levels were conservative (+/-10% on-axis), medium (+/-20% on-axis) and liberal (all data included).

Table 4.26 Statistical significance at different levels of off-axis force allowance for push exertions without off-axis force (* and green indicates statistical significance)

Condition, Axis	Factors	Level of Off-Axis Force Allowance		
		Conservative (+/-10% on-axis)	Medium (+/-20% on-axis)	Liberal (all data)
FC to FF, x-axis (off-axis)	Condition	$F_{1,17} = 0.16$ $p = 0.6948$	$F_{1,17} = 0.00$ $p = 0.9687$	$F_{1,17} = 0.10$ $p = 0.7501$
	Force	$F_{9,152} = 1.22$ $p = 0.2869$	$F_{9,153} = 1.51$ $p = 0.1486$	$F_{9,153} = 2.58$ $p = 0.0087$*
	Condition*Force	$F_{9,117} = 1.21$ $p = 0.2959$	$F_{9,143} = 2.46$ $p = 0.0122$*	$F_{9,148} = 1.29$ $p = 0.2485$
FC to FF, y-axis (off-axis)	Condition	$F_{1,17} = 15.91$ $p = 0.0010$*	$F_{1,17} = 12.58$ $p = 0.0025$*	$F_{1,17} = 13.12$ $p = 0.0021$*
	Force	$F_{9,152} = 1.08$ $p = 0.3822$	$F_{9,153} = 1.09$ $p = 0.3720$	$F_{9,153} = 0.74$ $p = 0.6730$
	Condition*Force	$F_{9,117} = 2.46$ $p = 0.0132$*	$F_{9,143} = 1.11$ $p = 0.3575$	$F_{9,148} = 1.31$ $p = 0.2363$
CC to CF, x-axis (off-axis)	Condition	$F_{1,17} = 16.12$ $p = 0.0009$*	$F_{1,17} = 13.44$ $p = 0.0019$*	$F_{1,17} = 12.69$ $p = 0.0024$*
	Force	$F_{9,153} = 1.33$ $p = 0.2249$	$F_{9,153} = 3.48$ $p = 0.0006$*	$F_{9,153} = 3.38$ $p = 0.0008$*
	Condition*Force	$F_{9,106} = 1.38$ $p = 0.2068$	$F_{9,142} = 1.04$ $p = 0.4147$	$F_{9,148} = 1.58$ $p = 0.1277$
CC to CF, y-axis (off-axis)	Condition	$F_{1,17} = 1.25$ $p = 0.2799$	$F_{1,17} = 1.65$ $p = 0.2164$	$F_{1,17} = 1.77$ $p = 0.2013$
	Force	$F_{9,153} = 0.93$ $p = 0.5015$	$F_{9,153} = 1.02$ $p = 0.4277$	$F_{9,153} = 1.16$ $p = 0.3220$
	Condition*Force	$F_{9,106} = 1.96$ $p = 0.0518$	$F_{9,142} = 1.56$ $p = 0.1342$	$F_{9,148} = 1.45$ $p = 0.1713$

Table 4.27 Statistical significance at different levels of off-axis force allowance for pull exertions without off-axis force (* and green indicates statistical significance)

Condition, Axis	Factors	Level of Off-Axis Force Allowance		
		Conservative (+/- 10% on-axis)	Medium (+/- 20% on-axis)	Liberal (all data)
FC to FF, x-axis (off-axis)	Condition	$F_{1,17}$ = 41.09 p = <0.0001*	$F_{1,17}$ = 29.78 p = <0.0001*	$F_{1,17}$ = 30.00 p = <0.0001*
	Force	$F_{9,153}$ = 1.69 p = 0.0964	$F_{9,153}$ = 2.22 p = 0.0237*	$F_{9,153}$ = 2.15 p = 0.0283*
	Condition*Force	$F_{9,132}$ = 2.39 p = 0.0152*	$F_{9,149}$ = 1.77 p = 0.0778	$F_{9,151}$ = 1.69 p = 0.0965
FC to FF, y-axis (off-axis)	Condition	$F_{1,17}$ = 11.87 p = 0.0031*	$F_{1,17}$ = 12.66 p = 0.0024*	$F_{1,17}$ = 12.21 p = 0.0028*
	Force	$F_{9,153}$ = 1.93 p = 0.0512	$F_{9,153}$ = 3.28 p = 0.0011*	$F_{9,153}$ = 3.67 p = 0.0004*
	Condition*Force	$F_{9,132}$ = 1.31 p = 0.2367	$F_{9,149}$ = 1.19 p = 0.3076	$F_{9,151}$ = 1.14 p = 0.3389
CC to CF, x-axis (off-axis)	Condition	$F_{1,17}$ = 30.75 p = <0.0001*	$F_{1,17}$ = 23.44 p = 0.0002*	$F_{1,17}$ = 16.27 p = 0.0009*
	Force	$F_{9,153}$ = 3.59 p = 0.0004*	$F_{9,153}$ = 4.00 p = 0.0001*	$F_{9,153}$ = 4.90 p = <0.0001*
	Condition*Force	$F_{9,131}$ = 4.23 p = <0.0001*	$F_{9,147}$ = 5.87 p = <0.0001*	$F_{9,149}$ = 5.29 p = <0.0001*
CC to CF, y-axis (off-axis)	Condition	$F_{1,17}$ = 8.60 p = 0.0093*	$F_{1,17}$ = 7.33 p = 0.0149*	$F_{1,17}$ = 5.96 p = 0.0259*
	Force	$F_{9,153}$ = 1.58 p = 0.1260	$F_{9,153}$ = 1.31 p = 0.2345	$F_{9,153}$ = 1.03 p = 0.4226
	Condition*Force	$F_{9,131}$ = 0.80 p = 0.6156	$F_{9,147}$ = 0.74 p = 0.6676	$F_{9,149}$ = 0.88 p = 0.5409

When comparing across the three levels of force allowance, the constrained case was found to eliminate too much data, which in turn reduced significance. The medium level allowed for the best representation of the data without including extreme cases as the liberal level had. Further, previous studies, which examined the influence of off-axis forces on hand force during push exertions, had defined no off-axis force with a tolerance of +/- 20% of the on-axis force (Hoffman, Reed, & Chaffin, 2007b). For the conditions without off-axis force, the off-axis forces represented as a percent of the on-axis force was kept between -20% on-axis and +20% on-axis for push and pull exertions. This tolerance level was also applied during analysis to the maximum force trials for consistency.

For conditions without off-axis forces (FC and CC), the average off-axis forces along the up-down (x-axis) and left-right (y-axis) axes were kept slightly above or below zero (within +/-3% on-axis). The standard deviation was approximately 5% on-axis but the range (minimum to maximum value) was much larger due to the allowed tolerance (Table 4.28).

Table 4.28 Off-axis force variation during push and pull exertions for conditions without off-axis force

Off-Axis Force (% on-axis)		Push Condition		Pull Condition	
		Submax FC	Submax CC	Submax FC	Submax CC
Fx	mean (sd)	1.4 (5.3)	-1.8 (5.4)	2.4 (4.3)	0.3 (4.5)
	range	-15.7 to 15.4	-16.2 to 11.9	-13.4 to 19.4	-16.6 to 11.6
Fy	mean (sd)	-3.1 (5.9)	-0.4 (6.5)	-3.0 (4.2)	-2.5 (5.2)
	range	-19.9 to 15.2	-17.6 to 19.2	-17.8 to 7.9	-19.2 to 19.9

With the exception of five isolated cases, which were taken out of the processed data, all moments at the hand were minimized (as close to zero as possible) for conditions without off-axis forces (FC and CC). The standard deviation was also kept around zero at an average of approximately 0.3 Nm but the range (minimum to maximum value) was larger at an average of approximately +/-1.2 Nm (Table 4.29).

Table 4.29 Moment variation during push and pull exertions for conditions without off-axis force

Moment (Nm)		Push Condition		Pull Condition	
		Submax FC	Submax CC	Submax FC	Submax CC
Mx	mean (sd)	0.09 (0.18)	0.07(0.17)	-0.17 (0.25)	-0.10 (0.18)
	range	-0.35 to 1.36	-0.30 to 0.89	-1.78 to 0.33	-0.94 to 0.29
My	mean (sd)	-0.08 (0.62)	-0.36 (0.42)	0.15 (0.51)	0.31 (0.45)
	range	-1.76 to 1.80	-1.69 to 1.01	-1.62 to 1.51	-1.14 to 1.56
Mz	mean (sd)	0.03 (0.25)	-0.12 (0.36)	-0.05 (0.32)	-0.11 (0.36)
	range	-1.04 to 1.03	-1.74 to 0.67	-1.33 to 1.12	-1.35 to 1.63

4.5.4 Maximum Joint Capacity

Maximum joint capacity was measured during experimentation and used to scale joint moments to enable intersubject comparison for individual and across joints. The capacity was measured about anatomically relevant joint axes and in the constrained posture so that they were representative of the experimental conditions in which moments would be compared (for the constrained posture without and with off-axis force conditions).

Table 4.30 Comparison of obtained joint moment capacities to literature values (^one less participant for shoulder internal-external rotation)

Joint	Anatomically relevant axis	Maximum moment (Nm) mean (sd) n = 18	Value from literature (Nm)	Percent Difference (%)
Shoulder	Flexion	25.6 (6.2)	40*	-36
	Extension	27.7 (9.1)	33*	-16
	Internal Rotation^	19.8 (7.0)^	21*	-6
	External Rotation^	14.8 (4.7)^	19*	-22
	Abduction	27.0 (7.6)	37*, 34.9 (5.4)**	-27, -29
	Adduction	22.9 (7.1)	30*, 42.1 (5.4)**	-24, -84
Elbow	Flexion	32.5 (12.5)	41*, 31.9 (5.5)**	-21, 2
	Extension	24.4 (7.1)	27*, 25.0 (2.2)**	-10, -2
	Supination	6.3 (1.6)	4.9 (1.6)***	22
	Pronation	6.7 (2.7)	4.7 (1.7)***	30
Wrist	Flexion	3.3 (1.6)	10.7 (2.7)**, 7.1 (2.3)***	-69. -115
	Extension	2.7 (1.3)	6.4 (0.9)**, 6.2 (1.8)***	-58, -130
	Radial Deviation	3.7 (1.4)	6.2 (2.7)***	-40
	Ulnar Deviation	2.9 (1.8)	7.7 (1.9)***	-62

*Moment values are the 50th %-ile of a female population (n=22) (Chaffin, Andersson, & Martin, 2006)

**Female participants, n=5, power grip, shoulder abduction-adduction posture: shoulder at 60 degree abduction, elbow extended, forearm in neutral rotation, and wrist in neutral flexion and deviation; elbow extension-flexion posture: elbow in 90 degree flexion, forearm supinated, shoulder in neutral abduction, and wrist in neutral posture; wrist extension-flexion posture: wrist in a neutral posture, forearm pronated, shoulder in neutral abduction, and elbow flexed to 90 degrees; participants were seated and torso restrained with straps placed around the trunk (Holzbaur, Delp, Gold, & Murray, 2007)

***Female participants, n=10, power grip, arm adducted against their side, elbow flexed to a 90 degree angle and wrist positioned midway between pronation and supination with slight extension (Greig & Wells, 2004)

V. Discussion

The results enable focused evaluation of the stated study hypotheses. The first hypothesis examined the impact of the four experimental conditions on the maximum on-axis force produced. The next two hypotheses pertained to quantifying off-axis force changes during different conditions and across submaximal force levels. The final hypothesis addressed specific changes in joint moments of the upper extremity across submaximal force levels. The outcomes were interpreted in a biomechanical context as an attempt to describe human motion and interpret adopted strategies for force production. Next, limitations of the experiment, including evaluating the intrinsic quality of the experimental data is discussed in relation to how precisely defined experimental conditions were met. Finally, future avenues of research are presented and overall study conclusions reviewed.

5.1 Hypothesis 1

Hypothesis 1 stated that maximum producible force in the on-axis direction would decrease as posture was constrained and off-axis force was not allowed. This hypothesis was tested by comparing normalized maximum producible on-axis force as percent of body weight (% BW) across all four experimental conditions.

The hypothesis was supported for both pushing and pulling exertions as maximum on-axis force significantly decreased when off-axis force was not allowed in the experimental conditions. These results are consistent with literature, as when off-axis forces were not allowed, maximum on-axis force production decreased (Seo & Armstrong, 2009) (Grieve & Pheasant, 1981) (Bober, Kornecki, Lehr, & Zawadzki, 1982). Specifically, the maximum on-axis push and pull force was on average 38% higher when off-axis force was allowed compared to not (Seo & Armstrong, 2009), and, for a for a fixed arm posture, was 20% higher when only vertical off-axis force was allowed and 26% higher when only horizontal off-axis force was allowed compared to when no off-axis force was allowed (Bober, Kornecki, Lehr, & Zawadzki, 1982). Thus, producing off-axis forces enables production of higher maximum on-axis force.

Further, the reduction in maximum on-axis force from the free posture with off-axis force condition to the free posture without off-axis force condition was similar for both pushing and pulling at 33% and 32%, respectively. This was also true when posture was constrained and off-axis force was not allowed, as the reduction in maximum on-axis force was 45% different for pushing and 43% different for pulling. For pushing, this reduction from with to without off-axis force was statistically significant when posture was constrained. In comparison, for pulling this reduction was not statistically significant whether posture was free or constrained. In fact, for pulling exertions, constraining only posture resulted in significantly higher on-axis force than constraining only off-axis force and constraining both posture and off-axis force (Figure 4.2). Thus, for pulling, allowing off-axis force was more influential on maximum on-axis force production than allowing for postural flexibility.

The hypothesis was further supported for both pushing and pulling exertions, as maximum on-axis force significantly decreased when posture was constrained in the experimental conditions. The reduction in maximum on-axis force from the free posture with off-axis force condition to the constrained posture with off-axis force condition had the same absolute reduction for pushing and pulling at 4.1% BW. Interestingly, the influence of this reduction was greater for pushing compared to pulling, with values of 22% and 15% difference, respectively, between the constrained and free posture with off-axis force conditions. As previously mentioned, for pushing exertions, constraining just posture was not statistically different from just not allowing off-axis force; as such posture had a similar effect on maximum pushing exertions as constraining off-axis force. In fact for pushing exertions, constraining posture and not allowing off-axis force was statistically lower than any other condition. These statistical relationships differed from results for pulling exertions. Thus, the chosen constrained posture had more influence in reducing the maximum on-axis force for pushing compared to pulling exertions. This is consistent with literature as in a flexed elbow posture mean maximum pull force was 26% greater than mean maximum push force during unilateral exertions (Seo, Armstrong, & Young, 2010). This was because in the flexed posture pushing required elbow extension strength whereas pulling required elbow flexion strength (Seo, Armstrong, & Young, 2010), and elbow flexion is approximately 25% greater than elbow extension strength (Holzbaur, Delp, Gold, & Murray, 2007).

5.2 Hypothesis 2

Hypothesis 2 stated that as required submaximal on-axis force level was increased, the presence of off-axis force would also increase for pushing and pulling exertions. This hypothesis was tested by comparing force along each of the off-axes as percent of on-axis force (% on-axis) between the free posture without off-axis force and free posture with off-axis force conditions across all required submaximal force levels.

For pushing exertions, when off-axis force was allowed, participants pushed to the left by a difference of 5.6% on-axis compared to when off-axis force was not allowed (Figure 4.3). This difference was consistent across all submaximal force levels and appears to be increasing as it was approaching the required force level of 50% max but this was not significant. Further, as submaximal force level increased, upward off-axis force also increased when it was allowed compared to when it was not allowed, where it remained close to zero (Figure 4.4). These rates of change were significantly different but there was no significant difference found between the two conditions in the tested submaximal force range. Both of these observations partially support the hypothesis as off-axis force was present but did not significantly increase within the tested submaximal force range. Conversely, the hypothesis was not supported for pulling exertions as both downward and rightward off-axis force significantly decreased as required submaximal force level increased. This decrease was consistent whether off-axis force was allowed or not. Thus, when off-axis force was allowed there was a difference of 12.6% on-axis downward and 4.7% on-axis rightward off-axis force compared to when it was not allowed (Figures 4.5 and 4.6).

Handle height has been demonstrated to largely dictate the presence of off-axis forces along the up-down axis. Lower handle heights (below elbow or waist height) have been associated with downward off-axis force during pushing and upwards off-axis force during pulling, and higher handle heights (shoulder height and above) have been associated with upward off-axis force during pushing and downward off-axis force during pulling (Boocock, Haslam, Lemon, & Thorpe, 2006) (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000) (Hoffman, Reed, & Chaffin, 2011) (Granata & Bennett, 2005) (Seo & Armstrong, 2009). Further, it is consistently reported that vertical off-axis force was either decreased, or minimal, between shoulder and waist heights (Ayoub & McDaniel, 1974) (Granata & Bennett, 2005). The chosen handle height was parallel to the xiphoid process of each participant, thus for pushing the observed slightly upwards off-axis force and for pulling downwards off-axis force is consistent with literature. Biomechanically, when comparing the no off-axis force to the free exertions, the presence of the observed vertical components of off-axis force acted to reduce external moments along the wrist radial-ulnar deviation and elbow flexion-extension axes and increase the external moment along the shoulder flexion-extension axis for both pushing and pulling exertions (Figure 5.1).

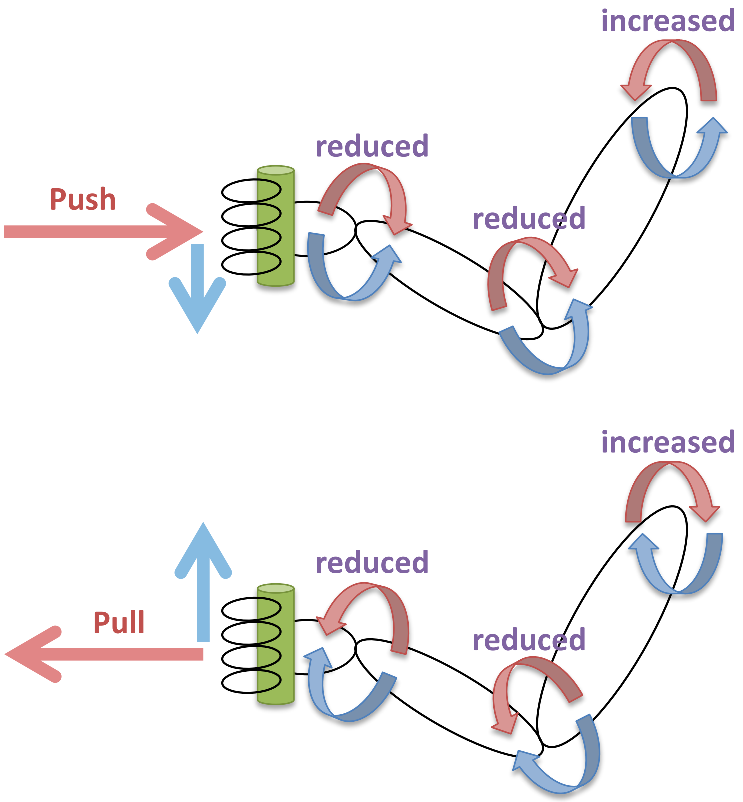

Figure 5.1 External joint moments (from handle proximally: radial-ulnar deviation at wrist, flexion-extension at elbow and shoulder) based on observed on- (red) and vertical off-axis (blue) reaction forces during pushing and pulling exertions in the free posture. Note: figure is not to scale and is for illustrative purposes.

This is based on the assumption that participants were exerting force in a flexed elbow posture with the elbow lower than the hand, which is reasonable based on the set distance from the handle to the participant and the constrained nature of the seated posture limiting variation in upper extremity posture. Further, the effect of the vertical off-axis force is more pronounced during pulling compared to pushing because the production of the vertical component of force is less limited by elbow strength during pulling in flexed elbow postures (Seo, Armstrong, & Young, 2010). This moment trade-off mechanism suggests that participants are choosing to target the shoulder and produce force using the shoulder flexion-extension muscle groups (deltoid, latissimus dorsi, serratus, and pectoralis major). Targeting of this muscle group has been demonstrated previously as during one-handed seated pushing and pulling exertions it was found that at submaximal force levels (40% and 60% maximum on-axis force) the deltoid was the task initiator (Bober, Kornecki, Lehr, & Zawadzki, 1982). Further, targeting specific musculature has also been observed during standing pushing and pulling exertions where increases in forward lean, and in turn the vertical component of off-axis force, have been used to engage torso musculature and use body weight to increase force (Granata & Bennett, 2005) (Hoffman, Reed, & Chaffin, 2011) (Okunribido & Haslegrave, 2008) (Wilkinson, Pinder, & Grieve, 1995) (Boocock, Haslam, Lemon, & Thorpe, 2006). Secondly, wrist strength has been suggested as limiting hand force production (Al-Eisawi, Kerk, & Congleton, 1998) (Bober, Kornecki, Lehr, & Zawadzki, 1982) (Seo & Armstrong, 2009). Also precluding elbow flexion-extension strength as limiting during one-handed pushing and pulling increases and allows for shoulder flexion-extension to contribute more to force production (Seo, Armstrong, & Young, 2010). Thus, employing vertical off-axis force to reduce external moments at the wrist and elbow is reducing the limiting effects of these joint strengths and allows the shoulder joint strength to be targeted. A similar mechanism has been observed during two-handed standing pushing and pulling exertions, where vertical off-axis force was used to reduce the limiting factor of floor friction and slip potential (Boocock, Haslam, Lemon, & Thorpe, 2006) (Ciriello, McGorry, & Martin, 2001) (Granata & Bennett, 2005) (Hoffman, Reed, & Chaffin, 2011).

Lateral off-axis forces have been described as minimal during pushing and pulling exertions (Seo & Armstrong, 2009) (Hoffman, Reed, & Chaffin, 2011). These studies positioned the handle such that it was inline with the hand and arm producing the force whereas the current study had the handle at the midline of the body. As such participants were exerting force across their torsos. This difference in handle position may explain the observed lateral components of off-axis force, as participants are tending to direct the force vector towards their elbow and shoulder joints when off-axis force was allowed. A similar mechanism has been observed during two-handed isometric pushing as participants modified their posture to align the axis of the spine with the external force vector to reduce the external trunk moment (Granata & Bennett, 2005) and during dynamic two-handed pushing and pulling as net shoulder moments were minimized by directing the line of action of the force slightly below the shoulder rotation axis (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000). Similar to previous literature in the current study, the lateral off-axis force is created to align the external force vector with the elbow supination-pronation axis as well as direct the line of action towards the shoulder joint, which reduces the external wrist flexion-extension, elbow supination-pronation, shoulder internal-external rotation and abduction-adduction moments (Figure 5.2).

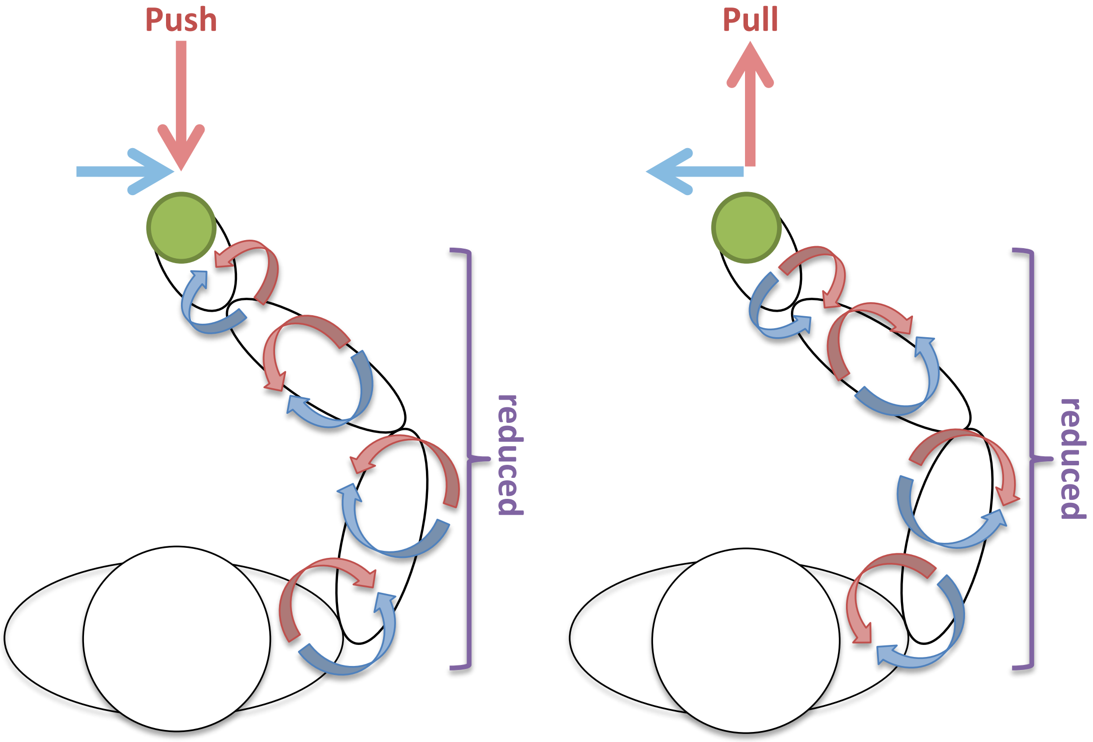

Figure 5.2 External joint moments (from handle proximally: flexion-extension at wrist, supination-pronation at elbow, internal-external rotation and abduction-adduction at shoulder) based on observed on- (red) and horizontal off-axis (blue) reaction forces during pushing and pulling exertions in the free posture. Note: figure is not to scale and is for illustrative purposes.

As previously mentioned, this is based on the assumption that participants were exerting force in a flexed elbow posture with the elbow lower than the hand, and strengthens the observed strategy of targeting the muscles associated with the shoulder flexion-extension moment.

During pushing, both upward and leftward off-axis force appeared to be increasing as required force level approached 50% max, indicating that at higher force levels these forces may be even more important to force production. This was qualitatively supported, as during experimentation participants found producing the no off-axis force condition more difficult as required off-axis force increased past 40% max. This was not found during pulling as both downward and rightward off-axis force significantly decreased as required submaximal force level increased to 50% max. Further, during experimentation, producing the no off-axis force condition was much easier for participants when pulling compared to pushing. These observations do not agree with literature as studies have found that increasing force level towards maximum increased the presence of off-axis forces for both pushing and pulling exertions (Granata & Bennett, 2005) (Hoffman, Reed, & Chaffin, 2011). The difference is few studies have tested submaximal (<50% max) force levels with small increments (5% max). As such, the results indicate that off-axis forces may be more important for pulling exertions compared to pushing exertions at submaximal force ranges (0% to 50% max on-axis).

5.3 Hypothesis 3

Hypothesis 3 stated that if posture was constrained, the production of off-axis force would increase as the normalized exertion level increased. This would be in response to reduced postural flexibility, as participants would not be allowed to use postural adjustments to achieve the required force exertions. This hypothesis was tested by comparing force along each of the off-axes between the constrained posture with off-axis force and free posture with off-axis force conditions across all required submaximal force levels from 5% max to 50% max.

When posture was constrained during pushing exertions, slightly upward off-axis force became downward off-axis force and the difference was a constant 12.9% on-axis (Figure 4.7). Further, for both constrained and free postures, the downward off-axis force decreased and the upward off-axis force increased, respectively, as required submaximal force level increased. No change was observed in off-axis force along the left-right axis when posture was constrained compared to when it was not. In comparison, when posture was constrained during pulling exertions, there was less downward off-axis force compared to the free posture and this difference increased as required submaximal force level increased (Figure 4.8). For both conditions downward off-axis force significantly decreased as required submaximal force increased but the rate of change was significantly greater for the constrained posture compared to the free posture. In fact, for the constrained posture, downward off-axis force became slightly upward off-axis force at the required force level of 50% max. Similarly, the rate of change for the rightward off-axis force was different for the constrained posture compared to the free posture. This difference was not in the magnitude but in the direction of the rate of change as when posture was constrained rightward off-axis force increased and when the posture was free it decreased as the required submaximal force level increased. The results for pushing and pulling do not support the hypothesis, as off-axis force did not increase when posture was constrained.

As previously noted during maximal on-axis exertions, the chosen constrained posture had a similar effect on on-axis force for both pushing and pulling (a 4% BW drop in on-axis force). This was partially seen during submaximal exertions where off-axis force for both pushing and pulling in the constrained posture was downward and significantly decreased as submaximal force level increased. This similarity in force direction during pushing and pulling indicates that the chosen upper extremity posture forces participants to push and pull in a downward direction, which decreases as force level is increased to 50% of maximum. Although similar in outcome, the observed change in vertical off-axis force from the free posture to the constrained posture was different for pushing and pulling exertions. For pushing, slightly upward off-axis force became downwards and for pulling downwards off-axis force became less downwards. When comparing joint moments changes in response to the change in resultant force direction, a unifying strategy is observed such that, compared to the free posture the shoulder flexion-extension moment is being less targeted. In fact, for pushing, the strategy is reversed as there is an increase in the internal elbow extension and wrist ulnar deviation moments, and a corresponding decrease in the internal shoulder flexion moment (Figure 5.3).

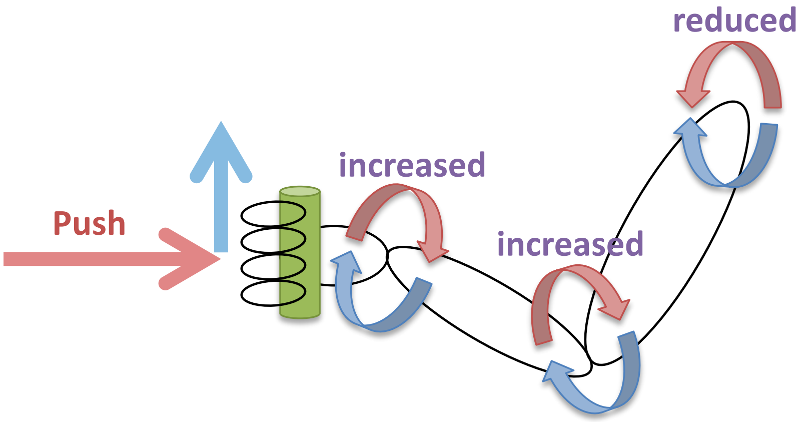

Figure 5.3 External joint moments (from handle proximally: radial-ulnar deviation at wrist, flexion-extension at elbow and shoulder) based on observed on- (red) and vertical off-axis (blue) reaction forces during pushing exertions in constrained posture. Note: figure is not to scale and is for illustrative purposes.

Increases in downwards off-axis force have been attributed to engaging torso musculature and, during standing exertions, engaging body weight by increasing forward lean (Granata & Bennett, 2005) (Wilkinson, Pinder, & Grieve, 1995). As such, participants changing pushing direction from slightly upward to downward indicates a similar change in muscle strategy and, since participants were constrained at the chest, shows that the constrained posture may act to target elbow flexion-extension and wrist radial-ulnar deviation strength over shoulder flexion-extension strength. For both pushing and pulling, the observed changes in the resultant force direction are in response to producing the required submaximal force level while maintaining the chosen constrained posture. As such, it indicates that the constrained posture is limited by shoulder flexion-extension strength. Biomechanically, the constrained posture has the elbow lateral from the torso and the place of force application, which would increase the necessary shoulder abduction-adduction moment to maintain this elbow position, limiting the ability of the deltoid to be used primarily to produce a pushing or pulling force, as was the observed strategy in the free posture.

On the contrary, constraining posture during pulling compared to pushing had a different effect on off-axis force along the left-right axis. For pulling exertions, there was a change in the direction of the rate of change of rightward off-axis force from decreasing to increasing when posture was constrained. In comparison, constraining posture during pushing had no significant effect on the leftward off-axis force compared to the free posture. Since the overall direction of the horizontal off-axis force did not change during pushing and pulling, the moment reduction strategy observed in the free posture is the same and participants are directing the resultant force towards the elbow and shoulder joints (Figure 5.2).

Interestingly, for pulling, constraining posture did not change the direction of the horizontal off-axis force but there was a trade-off between the vertical off-axis force magnitude (less downwards) and the horizontal off-axis force rate of change (decreasing to increasing) when posture was constrained. It appears that less reliance on the internal shoulder extension moment (indicated by the decrease in downwards force) corresponded with an increasing reduction in the internal wrist flexion, elbow supination, and shoulder internal rotation and adduction moments as submaximal force level increased to 50% of the maximum on-axis force. Wrist flexion strength is reportedly 10.5% stronger in extended wrist postures compared to neutral ones (Al-Eisawi, Kerk, & Congleton, 1998) and have a higher prevalence of medial-lateral off-axis forces compared to flexed wrist postures (Okunribido & Haslegrave, 2008). Further off-axis forces have also been suggested as agents to reduce external wrist moments to allow muscles of the elbow and shoulder to produce force (Bober, Kornecki, Lehr, & Zawadzki, 1982). Specifically, one study observed that in extended wrist postures and when exertion about the wrist was in the flexion direction (as is the case with pulling), wrist strength limited maximal elbow moments (Al-Eisawi, Kerk, & Congleton, 1998). As such, it would be imperative during pulling in the constrained posture (since the wrist is extended) to create horizontal off-axis force to reduce the external wrist moments especially as required force level is increased. Further, since a decrease in downward off-axis force would increase reliance on the internal elbow flexion moment, it would follow that in the constrained posture, compared to the free one, reducing external wrist moments is important to allow increased reliance through increased joint capability on this moment.

During two-handed, standing pushing and pulling, a protective strategy for the shoulder was alluded to as a reason to why participants were exerting force in bent elbow postures (Hoffman, Reed, & Chaffin, 2007a). Similar protective strategies during two-handed isometric pushing were observed at the L5/S1 joint where increasing vertical off-axis force increased external stability (Granata & Bennett, 2005). Although achieved in different ways for pushing and pulling, the unifying strategy of using less shoulder flexion-extension strength by targeting wrist and elbow moments appears to correspond to previously suggested protective shoulder strategies and indicates that the enforced constrained posture is limited by shoulder strength. Off-axis forces were changed to account for this limitation and thus depend on upper extremity posture.

5.4 Hypothesis 4

Hypothesis 4 stated that as normalized exertion level was increased in the constrained posture, normalized joint moments would be reduced when off-axis force was allowed compared to when it was not allowed. This change would correspond to manual force producing strategies that reduced the overall impact of the exertion on specific joints and/or employed a change in the use of specific muscle groups. This hypothesis was tested first by comparing force along each of the off-axes between the constrained posture without off-axis force and constrained posture with off-axis force conditions across all required submaximal force levels from 5% max to 50% max. Constrained posture conditions were used so that postural changes did not impact the outcomes of the off-axis forces and so that off-axis forces could be directly related to observed moment changes. Next, the moments were compared across these same conditions to themselves and related back to observed changes in the force production to determine overall biomechanical effects of off-axis forces.

For pushing exertions, there was significantly more downward off-axis force when off-axis force was allowed compared to not allowed in the constrained posture (Figure 4.10). The downward off-axis force decreased as required submaximal force increased whether off-axis force was allowed or not. On the contrary, in the constrained posture no significant difference in off-axis force along the left-right axis was found whether off-axis force was allowed or not. These observed changes in force direction corresponded to significantly higher elbow extension moment when off-axis force was allowed compared to when it was not allowed (Figure 4.13). Biomechanically, this is logical, as upward reaction force would increase the external flexion moment at the elbow thus requiring an increased internal extension moment. The observed significantly higher elbow extension moment when off-axis force was allowed shows that participants were targeting this moment to enhance pushing exertions in the constrained posture. This supports the hypothesis and moment strategies deduced from the results of Hypothesis 3. Further, similar relationships between vertical off-axis force and elbow flexion-extension moment have been reported for pushing and pulling exertions. Specifically, downwards reaction force during one- and two-handed pushing exertions reduced the elbow extension moment (Hoffman, Reed, & Chaffin, 2007a) (Seo, Armstrong, & Young, 2010).

For pulling exertions, there was significantly more downward off-axis force when off-axis force was allowed compared to not allowed and this difference decreased as required submaximal force level increased (Figure 4.11). In fact, this difference was nearly zero at the higher force levels of 40% to 50% of maximum on-axis force. In comparison, there was significantly more rightward off-axis force when off-axis force was allowed compared to not allowed in the constrained posture (Figure 4.12). This difference was consistent across all tested submaximal force levels but appears to increase past 50% of maximum on-axis force (Figure 4.12). Compared to pushing exertions, there were more observed significant differences noted in the measured moments during pulling. This shows that during pulling exertions, participants were more reliant on off-axis forces to modulate moments and, as observed during maximal exertions, pulling exertions were more sensitive to changes in off-axis force. Specifically, significantly less shoulder extension and more shoulder adduction moment were observed when off-axis force was allowed compared to not (Figures 4.14 and 4.15). The observed less internal shoulder extension moment follows with previous observations in Hypothesis 3 that less downwards off-axis force in the constrained posture reduces the external shoulder flexion moment. In fact, although not significant it appears that the downward off-axis force was becoming upwards with increasing required force level. Upwards off-axis force during pulling has been observed as a strategy to reduce shoulder moments as it directs the resultant force vector towards the shoulder joint (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000) (Hoffman, Reed, & Chaffin, 2011). On the contrary, pulling less downward and to the right created higher internal shoulder adduction moment compared to pulling straight back. This is counterintuitive to what rightward off-axis force would do (Figure 5.2). As previously mentioned, pulling to the right should act to reduce the internal shoulder adduction moment but this assumes that joints distal to the shoulder are not contributing to off-axis forces, which is not the case. As previously observed in literature, extended wrist postures have a higher prevalence of medial-lateral off-axis forces compared to flexed wrist postures (Okunribido & Haslegrave, 2008). As such, the right off-axis force could be primarily caused by flexion-extension at the wrist and is only mildly effecting the internal shoulder adduction moment. Further, it was observed that having the elbow away (anteriorly and laterally) from the body in the constrained posture reduced the effectiveness of shoulder extension strength to enhance pulling force (Hypothesis 3). Thus, it follows that when the arm is in the constrained posture, force would have to be derived from another muscle group to compensate for the lack of postural shoulder extension strength. This was further supported as the internal shoulder extension moment was reduced, suggesting that during pulling shoulder adduction strength was compensating for this moment. A similar moment trade-off was identified between the L5/S1 and the shoulder joints during full body pushing and pulling exertions (De Looze, Van Greuningen, Rebel, Kingma, & Kuijer, 2000). Further, internal elbow supination moment changed from more to less when off-axis force was allowed compared to not and the difference significantly increased with increasing required force level (Figure 4.16). Similarly, at the wrist, internal flexion moment was significantly less when off-axis force was allowed compared to not and this difference significantly increased as required force level increased (Figure 4.17). Both of these changes corresponded to the observed rightwards off-axis force as, in the constrained posture, pulling to the right decreased the external elbow pronation moment and wrist extension moment (Figure 5.2). Although not quantified nor monitored, the constrained posture places the forearm in slight supination. This means that a component of the decreasing downwards off-axis force would act to increase the internal supination moment and accounts for the observed change in internal elbow supination moment from more to less as required force level increased. Thus, rightward off-axis force was used to reduce moments at the wrist and elbow to increase force production driven from stronger muscles of the elbow and shoulder (ie/ muscles associated with elbow and shoulder flexion, and shoulder adduction). Similar strategies have been observed previously, especially for extended wrist postures, where wrist strength limited the exertion of maximal moments at the elbow for flexion exertions (Al-Eisawi, Kerk, & Congleton, 1998) and off-axis forces were used to reduce external wrist moments to allow muscles of the elbow and shoulder to produce force (Bober, Kornecki, Lehr, & Zawadzki, 1982). All of the aforementioned observations indicate that the hypothesis was supported for pulling exertions as moments changed (increased and decreased) with changes in off-axis force, indicating a joint-level moment control strategy.

Further, all of the moments for both pushing and pulling had a main effect of force. This means that as the required submaximal force level increased, so did each of the moments. Whether this increase was positive or negative depended on the moment direction (i.e. if the moment was negative, it became more negative and vice versa) and is biomechanically plausible as forces and moments are positively correlated. This further shows that regardless of off-axis force production, the main force in the on-axis direction had the largest influence on moments and that off-axis forces may be used more for fine-tuning of moment distributions compared to large reductions in resultant force production.

5.5 Integration of Hypothesis Results

When examining the results across Hypotheses 2-4, strategies as to how participants changed their off-axis force production can be discerned. There were essentially two strategic options available to participants to manipulate force direction: by changing their upper extremity posture and by using different muscles to enable force production. Significant differences across all conditions for vertical off-axis force during pushing and pulling, and horizontal off-axis force during pulling existed. This indicates that force in these directions is dependent upon both upper extremity postural adjustments (Hypothesis 2 and 3) and differential muscle use (Hypothesis 4). The same was not true for horizontal off-axis force during pushing. First, in the constrained posture no significant difference in horizontal off-axis occurred whether off-axis force was allowed or not (Hypothesis 4), which showed that using different muscles to produce force did not influence horizontal off-axis force since postural adjustments were not allowed during these conditions. Second, when posture was free and off-axis forces were allowed and not allowed (Hypothesis 2), there was a significant difference in horizontal off-axis force. Although when off-axis force production was compared for the constrained and free postures (Hypothesis 3) there was no significant difference in horizontal off-axis force, this may have been because a similar posture was adopted between the free and constrained postural conditions. Thus, horizontal off-axis force was directly affected by postural adjustments over force adjustments during pushing. Similar data emerged for maximal on-axis pushing (Hypothesis 1), were postural flexibility had a greater influence on on-axis force production compared to the presence of off-axis forces. Further, this is supported by the literature, as for two-handed full body pushing exertions (pulling exertions were not studied), “the ability to progressively change configuration of arm posture [was] important for effective performance” (Okunribido & Haslegrave, 2008). As previously mentioned, horizontal off-axis force during pushing helps to reduce moments at the wrist, elbow and shoulder (Figure 5.2). Further, it was qualitatively observed that achieving the required experimental conditions was harder for participants during pushing exertions compared to pulling exertions, and this is linked to the limiting effects of reduced postural flexibility on horizontal off-axis force during pushing exertions. These observations are important to consider when designing work tasks since allowing for horizontal off-axis force (via upper extremity posture or postural flexibility) can reduce the difficulty of pushing tasks, and in turn reduce muscular demand and the potential for fatigue and injury.

5.6 Limitations

Three sets of limitations are discussed. The first set pertains to how well each of the experimental conditions were met and how this may have affected the results. The second set, are assumptions made throughout the experiment that could have affected the outcomes. The third set pertains to the generalizability of the results and conclusions.

5.6.1 Verification of Experimental Conditions

The first limitation pertains to achieving the specified experimental conditions. A drop-off in achieving the required level of force existed for both directions (Tables 4.35 and 4.36). This drop-off was more pronounced for the pulling conditions where it started to be greater than 2% max at 35% max to 50% max in comparison to pushing where it was at this level for 45% max and 50% max. This may have affected the results, as there was a lowering in the total force being exerted compared to what was required. Overall, this would mean that observed trends in the data would have been understated. The required force level was monitored during experimentation via the visual feedback and a second investigator but for future experiments the resolution of the visual display should be increased for better accuracy.

Secondly, variation in the angles during the constrained posture conditions could have also affected the outcomes. For both pushing and pulling exertions, there were large standard deviations (10-15 degrees) for the shoulder plane of elevation angle and wrist extension angle (Tables 4.37 and 4.38). Again this was more evident for pulling compared to pushing. It also appears that for the certain angles, the actual values differed from the measured values during experimentation. In particular, for pushing, shoulder elevation was on average 5 degrees greater than the expected 30 degrees, elbow included angle was 15 degrees lower than the expected 100 degrees, and wrist included angle was 20 degrees higher than the expected 140 degrees. For pulling, elbow included angle was 13 degrees lower than the expected 100 degrees and wrist included angle was 20 degrees higher than the expected 140 degrees. Even though these differences were large, they were consistent across conditions that were being compared and thus represent a “constrained posture” and should not invalidate the overall meaning of the results.

Thirdly, for both pushing and pulling exertions, the off-axis forces represented as a percent of on-axis were evaluated to see if the original range of +/-10% on-axis was applicable. It was found that limiting these forces to this range, not only eliminated many data points, it also had no impact on overall statistical significance (Tables 4.39 and 4.40). As such, the range that was used was +/-20% of the on-axis force level. With this new range of included off-axis force values, there was relatively low standard deviation across conditions (approximately 5% on-axis) (Table 4.41). This indicated that even though larger off-axis force values were included for a more complete data set, it did not negatively affect the overall spread of the results, as these larger values were minimal.

Finally, it is noted that for the elbow supination-pronation, wrist flexion-extension and wrist radial-ulnar deviation moments, there were scaled values which were over 100% maximum. This indicates that for these moments, the true maximum capacity of the joints was not obtained in the reference measurements. With the exception of the elbow supination-pronation moments, all measured maximum moments tended to be lower when compared to previous literature (Table 4.30). These differences are related to two differences between the upper extremity postures in literature and the one used in the experiment. The first was that the elbow was at 100 degree included angle compared to the 90 degrees used in literature. The second was that the wrist was extended in the constrained posture compared to neutral. It has been shown in literature that force production is highly dependent on both elbow and wrist postures (Al-Eisawi, Kerk, & Congleton, 1998) (Bober, Kornecki, Lehr, & Zawadzki, 1982) (Okunribido & Haslegrave, 2008) (Hoffman, Reed, & Chaffin, Predicting Force-Exertion Postures from Task Variables, 2007a). As such, it follows that the chosen constrained posture was not optimal for moment production along these axis and accounts for why some of the measured moments were over 100%. The moments with the highest percent difference between the experimental and literature values were wrist flexion-extension and radial-ulnar deviations moments. Elbow flexion-extension and shoulder internal-external rotation, abduction and extension, tended to be closest to the values taken from literature at less than 20% difference. Finally, elbow supination-pronation values were the only moments higher than the values taken from literature and may be related to the equipment used during experimentation and lack of isolation of this moment. Specifically, since the wrist was extended, force driven from wrist flexion-extension moment may have increased the ability to produce supination-pronation moment that would not have existed in a neutral wrist posture. In fact, one study did not use a power grip to measure supination-pronation but instead used a custom wrist clamp, and found much lower values (1.19 and 1.20 Nm, respectively) than seen in any other literature (Gordon, Pardo, Johnson, King, & Miller, 2004).

5.6.2 Experimental Assumptions

First, when adding the hand force to the model in Visual 3D, it was assumed that external forces and moments were acting at the center of gravity of the hand. This could have influenced the moment calculations if this location was slightly different in reality. Second, even though it was monitored during experimentation, it was assumed that each participant gripped the force handle at the center of the handle for each exertion. This may not have been the case each time.

5.6.3 Generalizability of the Results

The results and conclusions are limited by their generalizability across populations and experimental conditions. First, only data from female participants was collected. It is known that females and males have different strengths as well as postural adaptations during pushing and pulling exertions (Chaffin, Andersson, & Martin, 2006). As such, the aforementioned observations are limited to applicability to females and may be different for males. The second limitation is that all exertions were performed seated, constrained at the chest, static, in one handle location, and one-handed with the dominant hand. These limitations must be considered when generalizing the results to other types of pushing and pulling exertions (i.e. two-handed or standing exertions) and may account for some differences in the results when comparing to other studies.

5.7 Future Directions

First, there was large variability between participants as there were, in some cases, large standard deviations in the data. For the majority of cases, these standard deviations were not bi-directional indicating that even though variable, employed force producing strategies were consistent across participants. In literature, it was found that standard deviation in off-axis force tended to increase as required force level increased (Hoffman, Reed, & Chaffin, 2011). The opposite was found during this study as lower required force levels tended to have lower standard deviations, which perhaps indicates that participants were converging on force production strategies as force increased. This observed difference from literature was because the aforementioned study had a less homogenous participant group (10 males and 10 females) and provides support to theories that males and females produce force using different strategies. Overall, a larger sample size would help to determine if these variations are random or systematic. Further, male data would be useful for sex comparisons. From an ergonomics perspective, it would be interesting to evaluate the data to specifically determine the effects of off-axis force on joint capabilities of the upper extremity. Conceptually, this could be completed using an ergonomic evaluation program such as the 3D Static Strength Prediction Program (University of Michigan, Ann Arbor, USA). A related question is how off-axis force is modified when the position of the force handle is changed instead of the required force magnitude. This would lead to comparisons between whether handle position or force characteristics have a greater influence on off-axis forces. From a biomechanical perspective, electromyographical (EMG) data on similar exertions would be useful to identify specific muscle contributions and their association with changing joint moments. Further, it was noted during experimentation that participants with scapular winging tended to have a harder time completing the constrained conditions. It would be interesting to group participants based on initial scapular position or functional strength in different static positions of the shoulder to determine if these factors correlate with the production of off-axis forces.

VI. Conclusions

Comparing across different experimental conditions and force intensities, and examining the resulting changes in maximum on-axis force, off-axis force and upper extremity joint moments, the following conclusions were made:

1. When experimental conditions are constrained, maximum on-axis force decreased. For pulling exertions, allowing off-axis force was more influential on maximum on-axis force production than allowing for postural flexibility. Further, the chosen constrained posture had more influence in reducing the maximum on-axis force for pushing than pulling exertions.

2. In the free posture, participants tended to use off-axis forces to target and drive force production from the shoulder flexion-extension moment during pushing and pulling exertions. Further, the trends of off-axis force production as required submaximal force was increased, indicated that off-axis forces might be more important for pulling exertions than pushing exertions in submaximal force ranges (0% to 50% max on-axis).

3. Constraining upper extremity posture resulted in reduced targeting of the shoulder-flexion extension moment for both pushing and pulling exertions. For pushing exertions, this was achieved by inverting the vertical off-axis force direction from upwards to downwards when posture was constrained resulting in an increase in the internal elbow extension and wrist ulnar deviation moments, and a corresponding decrease in the internal shoulder flexion moment. For pulling, this was achieved by a decrease in downwards off-axis force and increasing rightward off-axis force resulting in less reliance on the internal shoulder extension moment (decrease in downward force) corresponding to increasing reduction in the internal wrist flexion, elbow supination, and shoulder internal rotation and adduction moments (increasing rightward force). Even though achieved in different ways for pushing and pulling, the unifying strategy of using less shoulder flexion-extension strength by targeting wrist and elbow moments appears to follow with literature on protective shoulder strategies and indicates that the chosen constrained posture was limited by shoulder strength. Off-axis forces were changed to account for this limitation and thus depended on upper extremity posture.

4. When examining the moments produced in the constrained posture with and without off-axis force, previously observed strategies were verified. For pushing exertions, the presence of downward off-axis force caused significantly more internal extension moment at the elbow when off-axis forces were allowed compared to not allowed and showed that participants were targeting this moment to drive pushing exertions in the constrained posture. For pulling exertions, allowing off-axis force resulted in significantly less internal shoulder extension and more internal shoulder adduction moment showing that internal adduction moment was used to compensate for the lack of shoulder extension strength due to the constrained posture. Further, internal elbow supination moment changed from more to less when off-axis force was allowed compared to not and the difference significantly increased with increasing required force level. Similarly, internal wrist flexion moment was significantly less when off-axis force was allowed compared to not and this difference significantly increased as required force level increased. Thus, rightward off-axis force was used to reduce moments at the wrist and elbow to increase force production driven from stronger muscles of the elbow and shoulder (ie/ muscles associated with elbow and shoulder flexion, and shoulder adduction).

5. Finally, similar to maximal exertions, pulling exertions were more sensitive to changes in off-axis forces compared to pushing exertions as more significant changes in moments were observed during pulling compared to pushing. Further, it was observed that horizontal off-axis force during pushing was more sensitive to changes in posture compared to changes in off-axis force production. This supported similar observations during maximal exertions that pushing exertions were more sensitive to postural flexibility compared to pulling exertions.

The primary goal of this research was to provide information about force direction and changing force intensity during seated, unilateral push and pull exertions to help improve workplace design. Designing for true force directions, as opposed to assumed reaction forces, will improve overall design by increasing accuracy and ultimately reducing the potential for injury. Ergonomists can perhaps apply the specific results (as long the scenario approximates the experimental conditions) but more importantly use the aforementioned principles to help guide future workplace designs by accounting for the devised movement and moment strategies.

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Appendix A: Specific description of postures and attachment locations for joint moment capacity testing

Joint	**Moment**	**Handle Type**	**Subject Position**	**Arm Posture**	**Cuff Location**	**Parallel Axis**	**Perpendicular Axis**	**Subject Restraining**
Shoulder	Flexion	strap	seated in stool	upper arm in 30° plane, of elevation at 60° elevation	anterior side of upper arm	x-axis of the upper arm local coordinate system (LCS)	y-axis of the upper arm LCS	torso motion
	Extension				posterior side of upper arm			
	Abduction				lateral side of upper arm	z-axis of the upper arm LCS		
	Adduction				medial side of upper arm			
	Internal Rotation			upper arm in 30° plane of elevation, at 60° elevation, elbow at 100° included angle	medial side of forearm			torso motion and elbow motion at forearm
	External Rotation				lateral side of forearm			
Elbow	Flexion		standing	elbow at 100° included angle, upper arm at side	anterior side of forearm	x-axis of the forearm LCS	y-axis of the forearm LCS	upper arm motion
	Extension		seated in low stool		posterior side of forearm			
	Pronation	handle	seated in stool	elbow at 100° included angle, wrist at 140° included angle	power grip at middle of hand	z-axis of hand LCS	y-axis of hand LCS	
	Supination							
Wrist	Flexion							upper arm and forearm motion
	Extension							
	Radial deviation							
	Ulna deviation							

Appendix B: Tabulation of off-axis forces and joint moments across submaximal force levels

Table B.1 Off-axis force along the up-down and left-right axes for all four experimental conditions as percent on-axis force (% on-axis) at the required submaximal force levels of 5 to 50 percent maximum on-axis force (% max) for pushing exertions

Axis	Condition	Descriptive Statistic	Off-axis force during pushing exertions (% on-axis)									
			5% max	10% max	15% max	20% max	25% max	30% max	35% max	40% max	45% max	50% max
Up-down	FF	Average	-5.2	2.2	-3.3	0.2	3.3	7.5	7.2	0.7	4.2	3.7
		Std. Dev.	24.9	19.2	13.2	18.0	15.5	17.8	22.3	12.9	14.1	15.2
		n	17	18	17	18	18	18	18	18	18	18
	FC	Average	2.9	-0.1	1.8	0.5	2.8	3.1	2.0	0.4	0.5	0.2
		Std. Dev.	6.7	5.7	6.8	6.9	5.1	4.3	5.0	3.5	4.3	3.2
		n	14	17	18	17	18	18	18	18	17	17
	CF	Average	-22.6	-12.4	-12.5	-11.6	-10.8	-9.9	-8.9	-6.6	-6.5	-5.8
		Std. Dev.	33.3	13.9	18.1	10.9	13.2	13.3	10.8	11.9	13.7	8.9
		n	18	18	18	18	18	18	18	18	18	18
	CC	Average	-5.4	-1.4	-1.5	-2.1	-0.4	-1.8	-1.8	-0.5	-1.7	-1.9
		Std. Dev.	7.1	6.5	5.8	7.0	5.2	4.9	3.4	5.5	3.3	4.1
		n	15	15	17	18	18	18	18	18	16	16
Left-right	FF	Average	-11.7	-6.4	-4.4	-6.4	-8.2	-9.1	-9.1	-8.5	-10.7	-12.8
		Std. Dev.	20.7	11.2	9.6	12.5	10.9	8.7	11.5	11.2	8.9	10.7
		n	17	18	17	18	18	18	18	18	18	18
	FC	Average	-6.3	-3.4	-3.2	-1.0	-2.9	-2.2	-2.2	-3.6	-2.8	-3.6
		Std. Dev.	10.4	9.0	6.8	5.8	5.4	3.7	3.4	3.8	4.1	3.3
		n	14	17	18	17	18	18	18	18	17	17
	CF	Average	-9.1	-2.9	-1.9	-3.4	-0.8	-2.5	-10.0	-4.4	-4.4	-5.8
		Std. Dev.	30.9	22.9	13.7	15.8	12.9	11.7	13.3	17.1	13.3	12.4
		n	18	18	18	18	18	18	18	18	18	18
	CC	Average	3.4	0.3	0.4	0.1	-1.1	0.3	0.1	-3.9	-1.2	-2.3
		Std. Dev.	6.8	9.7	8.8	7.3	4.8	6.3	4.2	5.3	4.7	4.5
		n	15	15	17	18	18	18	18	18	16	16

Table B.2 Off-axis force along the up-down and left-right axes for all four experimental conditions as percent on-axis force (% on-axis) at the required submaximal force levels of 5 to 50 percent maximum on-axis force (% max) for pulling exertions

Axis	Condition	Descriptive Statistic	Off-axis force during pulling exertions (% on-axis)									
			5% max	10% max	15% max	20% max	25% max	30% max	35% max	40% max	45% max	50% max
Up-down	FF	Average	-17.5	-18.5	-18.1	-18.3	-13.5	-17.3	-15.4	-13.4	-10.2	-8.1
		Std. Dev.	21.9	19.0	13.9	14.1	8.2	10.9	12.7	12.2	12.3	10.4
		n	18	18	18	18	18	18	18	18	18	18
	FC	Average	-5.0	-3.5	-2.1	-2.2	-2.8	-2.0	-2.3	-0.4	-1.2	-2.6
		Std. Dev.	7.6	5.8	5.1	3.6	2.9	3.7	2.1	2.7	3.3	3.6
		n	16	18	18	18	18	18	17	18	17	18
	CF	Average	-21.8	-11.1	-8.3	-10.3	-7.1	-7.2	-7.9	-2.3	-3.3	1.3
		Std. Dev.	24.2	13.4	13.3	12.0	10.5	10.9	9.8	7.7	12.9	7.8
		n	18	18	18	18	18	18	18	18	18	18
	CC	Average	2.0	-1.5	0.1	-0.7	-2.0	-0.7	0.2	-0.2	-0.3	0.2
		Std. Dev.	6.5	5.5	4.4	5.0	4.1	3.0	4.2	3.8	3.5	3.6
		n	16	18	18	18	18	18	17	17	17	17
Left-right	FF	Average	13.1	9.1	8.5	8.0	5.8	5.0	5.6	8.2	7.0	6.2
		Std. Dev.	10.6	11.2	7.7	6.9	9.3	9.0	9.1	8.6	7.2	8.5
		n	18	18	18	18	18	18	18	18	18	18
	FC	Average	6.3	3.7	2.0	3.2	2.8	2.2	3.3	1.5	2.7	2.9
		Std. Dev.	6.7	4.0	5.0	4.4	1.9	2.9	4.1	3.9	4.0	3.0
		n	16	18	18	18	18	18	17	18	17	18
	CF	Average	2.5	4.6	6.0	8.4	5.4	6.7	8.6	7.5	10.8	9.3
		Std. Dev.	15.6	15.0	13.6	8.3	10.7	11.2	8.9	9.0	11.1	10.8
		n	18	18	18	18	18	18	18	18	18	18
	CC	Average	1.6	1.6	2.8	2.0	2.6	3.2	2.1	2.7	2.6	3.6
		Std. Dev.	8.4	8.6	5.5	3.5	4.7	4.2	3.7	3.6	4.0	4.2
		n	16	18	18	18	18	18	17	17	17	17

Table B.3 Moment about anatomically relevant joint axes for the constrained posture without off-axis force condition as percent maximum joint capacity in the constrained posture (% cap) at the required submaximal force levels of 5 to 50 percent maximum on-axis force (% max) for pushing exertions (*one less participant for shoulder internal-external rotation)

Moment	Descriptive Statistic	Moment during pushing exertions for the constrained posture without off-axis force condition (% cap)									
		5% max	10% max	15% max	20% max	25% max	30% max	35% max	40% max	45% max	50% max
Should Flexion-Extension	Average	-1.5	-2.6	-3.9	-5.2	-5.6	-7.5	-7.8	-7.1	-8.8	-9.1
	Std. Dev.	1.3	2.2	2.2	1.8	3.4	4.3	4.7	4.6	4.0	4.8
Shoulder Internal-External Rotation*	Average	-11.2	-16.1	-20.7	-25.3	-30.0	-34.9	-38.2	-40.8	-44.5	-47.1
	Std. Dev.	2.4	4.5	4.0	5.8	7.2	9.6	9.7	10.4	9.4	9.3
Shoulder Abduction-Adduction	Average	-11.5	-15.1	-17.9	-20.9	-24.0	-26.0	-28.5	-32.1	-33.5	-36.0
	Std. Dev.	3.7	5.5	6.4	6.8	8.3	8.6	9.7	10.6	10.4	11.3
Elbow Flexion-Extension	Average	0.5	1.0	1.4	1.6	2.0	2.6	3.6	4.7	4.4	5.3
	Std. Dev.	0.3	0.7	0.7	0.6	0.6	1.8	2.6	3.0	2.3	2.1
Elbow Supination-Pronation	Average	-25.2	-37.3	-45.5	-55.8	-67.0	-76.9	-86.3	-92.2	-101.0	-107.6
	Std. Dev.	6.7	12.0	13.1	13.2	17.6	21.5	23.7	29.0	27.5	29.3
Wrist Flexion-Extension	Average	5.9	10.1	15.0	22.2	25.2	36.6	43.7	56.8	54.5	75.9
	Std. Dev.	8.8	12.0	20.0	25.4	34.4	35.5	35.3	49.4	46.7	66.6
Wrist Radial-Ulnar Deviation	Average	-10.6	-22.6	-28.1	-33.5	-41.9	-47.8	-57.6	-58.1	-77.0	-83.7
	Std. Dev.	9.4	25.9	34.9	34.6	46.1	43.4	59.9	70.8	77.5	106.5
For all moments	n	15	15	17	18	18	18	18	18	16	16

Table B.4 Moment about anatomically relevant joint axes for the constrained posture with off-axis force condition as percent maximum joint capacity in the constrained posture (% cap) at the required submaximal force levels of 5 to 50 percent maximum on-axis force (% max) for pushing exertions (*one less participant for shoulder internal-external rotation)

Moment	Descriptive Statistic	Moment during pushing exertions for the constrained posture with off-axis force condition (% cap)									
		5% max	10% max	15% max	20% max	25% max	30% max	35% max	40% max	45% max	50% max
Should Flexion-Extension	Average	-0.4	-0.3	-0.1	-0.7	-0.4	-0.7	-0.5	1.8	-0.8	2.9
	Std. Dev.	10.3	16.3	20.7	24.3	29.8	33.4	38.7	43.7	47.6	56.7
Shoulder Internal-External Rotation*	Average	-10.5	-15.3	-20.3	-23.3	-29.0	-32.3	-33.1	-39.6	-43.5	-45.4
	Std. Dev.	2.9	4.3	4.6	6.0	9.5	7.6	7.6	12.8	14.7	9.4
Shoulder Abduction-Adduction	Average	-11.7	-14.4	-17.6	-20.3	-23.0	-26.0	-29.7	-31.8	-34.4	-36.7
	Std. Dev.	4.2	5.1	6.1	7.6	8.4	9.5	11.2	11.0	12.5	11.9
Elbow Flexion-Extension	Average	1.0	1.2	1.8	2.6	3.1	3.6	5.0	5.0	5.8	6.5
	Std. Dev.	0.7	1.0	0.9	1.3	1.8	1.8	3.3	3.0	3.6	3.1
Elbow Supination-Pronation	Average	-22.7	-33.7	-45.2	-52.4	-64.7	-72.9	-75.0	-88.3	-99.0	-103.2
	Std. Dev.	8.3	11.3	14.7	17.0	23.2	22.9	22.5	28.3	38.9	30.8
Wrist Flexion-Extension	Average	6.7	5.0	12.2	19.2	26.7	27.5	31.1	37.8	50.4	56.7
	Std. Dev.	8.1	9.5	14.0	16.9	13.8	31.7	30.7	38.5	33.2	31.1
Wrist Radial-Ulnar Deviation	Average	-7.5	-11.3	-19.1	-21.8	-29.2	-30.8	-34.0	-37.2	-41.7	-49.3
	Std. Dev.	9.9	9.4	17.1	20.8	26.2	32.3	37.5	43.5	48.9	55.2
For all moments	n	18	18	18	18	18	18	18	18	18	18

Table B.5 Moment about anatomically relevant joint axes for the constrained posture without off-axis force condition as percent maximum joint capacity in the constrained posture (% cap) at the required submaximal force levels of 5 to 50 percent maximum on-axis force (% max) for pulling exertions (*one less participant for shoulder internal-external rotation)

Moment	Descriptive Statistic	Moment during pulling exertions for the constrained posture without off-axis force condition (% cap)									
		5% max	10% max	15% max	20% max	25% max	30% max	35% max	40% max	45% max	50% max
Should Flexion-Extension	Average	2.3	4.3	6.2	8.5	9.5	11.9	13.7	15.2	17.1	19.3
	Std. Dev.	1.5	2.4	3.6	4.9	5.1	7.2	9.0	8.0	9.5	11.8
Shoulder Internal-External Rotation*	Average	2.3	7.1	13.1	17.5	22.5	27.9	32.9	38.4	42.8	45.2
	Std. Dev.	2.2	3.4	4.9	6.6	7.9	9.5	13.0	13.1	15.2	14.7
Shoulder Abduction-Adduction	Average	-3.5	-0.3	3.5	6.3	9.3	12.2	15.8	19.1	22.0	24.3
	Std. Dev.	1.7	2.3	2.6	3.1	3.4	4.1	5.9	7.0	7.0	7.5
Elbow Flexion-Extension	Average	-1.0	-1.5	-2.1	-3.2	-3.6	-4.2	-5.2	-6.6	-7.7	-8.0
	Std. Dev.	0.7	1.3	2.0	2.1	2.2	1.7	2.5	4.8	3.8	4.8
Elbow Supination-Pronation	Average	7.0	20.9	39.7	51.9	68.1	82.3	98.7	114.4	127.4	138.5
	Std. Dev.	6.0	10.1	16.2	21.0	28.3	28.7	42.2	43.4	47.5	55.5
Wrist Flexion-Extension	Average	-6.2	-8.8	-9.3	-19.3	-22.0	-23.1	-35.9	-36.9	-43.0	-55.9
	Std. Dev.	8.0	9.8	24.9	23.8	34.0	28.6	37.7	45.9	52.3	65.5
Wrist Radial-Ulnar Deviation	Average	5.3	11.7	21.3	24.3	29.9	37.4	45.1	52.5	55.1	67.7
	Std. Dev.	5.5	10.8	21.5	27.0	33.4	32.5	38.5	52.0	62.3	82.9
For all moments	n	16	18	18	18	18	18	17	17	17	17

Table B.6 Moment about anatomically relevant joint axes for the constrained posture with off-axis force condition as percent maximum joint capacity in the constrained posture (% cap) at the required submaximal force levels of 5 to 50 percent maximum on-axis force (% max) for pulling exertions (*one less participant for shoulder internal-external rotation)

Moment	Descriptive Statistic	Moment during pulling exertions for the constrained posture with off-axis force condition (% cap)									
		5% max	10% max	15% max	20% max	25% max	30% max	35% max	40% max	45% max	50% max
Should Flexion-Extension	Average	2.4	4.0	4.8	5.6	8.5	9.5	9.5	12.4	11.7	13.6
	Std. Dev.	2.4	3.0	5.3	4.9	9.2	9.1	8.4	8.7	14.0	15.7
Shoulder Internal-External Rotation*	Average	2.9	7.6	12.3	17.5	23.5	27.4	31.6	36.0	39.4	43.1
	Std. Dev.	3.0	4.9	5.0	7.7	10.2	10.7	10.1	12.4	16.0	14.7
Shoulder Abduction-Adduction	Average	-2.7	0.8	3.7	7.2	10.4	13.5	17.3	19.0	22.9	25.2
	Std. Dev.	1.9	2.5	2.6	4.0	4.3	5.4	5.5	6.5	9.1	7.8
Elbow Flexion-Extension	Average	-0.7	-1.5	-2.2	-2.8	-3.5	-4.2	-6.1	-7.5	-7.8	-9.8
	Std. Dev.	0.7	1.0	1.3	2.0	2.6	2.7	3.9	3.7	4.7	5.3
Elbow Supination-Pronation	Average	9.7	24.2	36.8	52.2	69.3	83.9	95.8	108.0	117.7	130.6
	Std. Dev.	8.5	15.5	18.1	24.6	32.8	36.5	38.0	41.5	51.6	57.2
Wrist Flexion-Extension	Average	-8.5	-13.5	-17.0	-19.6	-29.3	-39.7	-44.3	-62.4	-51.2	-74.0
	Std. Dev.	10.9	14.0	20.0	18.5	38.9	44.9	49.2	66.3	68.9	84.6
Wrist Radial-Ulnar Deviation	Average	9.9	18.2	26.7	34.6	46.4	65.5	59.3	78.8	68.9	92.3
	Std. Dev.	13.0	17.7	30.7	38.1	55.0	77.2	56.6	91.4	63.2	95.2
For all moments	n	15	15	17	18	18	18	18	18	16	16