A Comparison Between Different Handcuff Configurations

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Disclosure Statement by the Authors: The results and findings represented here are based upon independent research conducted by the study author(s); these findings do not represent endorsement of a specific product or service.

Abstract. *Handcuffs are a common law enforcement tool used to control and restrain individuals by restricting arm movement. The purpose of this study was to assess the differences between two different handcuff designs. Active law enforcement officers and trainees completed a two-visit protocol. In both visits two types of handcuffs - SpiderCuff and Smith & Wesson (SW) in both short- and long-configurations were used in random order. During the first visit, participants applied hand-cuffs to two 3D-printed arms: one attached to a dynamometer and the other attached to a stationary stand. In the second visit, kinematics and electromyography (EMG) of the shoul-der joint were captured while participants applied handcuffs to each other. Effect size differences between handcuff designs were evaluated within each condition with Cohen's d. Applying the SpiderCuff resulted in lower peak-torque than SW hand-cuff in both long- and short-conditions, and lower total impulse in the short- condition. For the short-condition, SpiderCuff required a lower range of motion during application and reduced net EMG activity of the muscles spanning the shoulder than SW. In the long-condition, SW resulted in lower peak shoulder adduction velocity than the SpiderCuff, and longer time of ap-plication. The new SpiderCuff handcuff design aims to improve safety for the parties involved during a routine handcuffing by reducing injury risk to the shoulder and reducing the time of application. The data in this study suggest that the shoulder joint and surrounding musculature are, on average, exposed to lower rotational torques over shorter ranges of motion when the SpiderCuff is applied, compared to SW; and while other results show mixed effects of which handcuff design performed better, the SpiderCuff demonstrated consistently stronger effects than SW across our variables of study.*

KEY WORDS: Shoulder Biomechanics; Handcuffs; Shoulder Muscle Activation.

1 Introduction

Handcuffs are a common law enforcement tool used to control and restrain a person-in-distress by limiting their movement in order to reduce the risk of injury to the officer, members of the public, and the individual being detained [1]. It is recommended that handcuffs be applied for the shortest period of time possible and tightened only to the extent that they achieve the restraint or control needed [1]. There are two typical ways handcuff bracelets are held together: 1) hinge and 2) chain [2, 3, 4, 5], with chain-connected cuff being most prevalent in the United States (Figure 1). If there are an insufficient number of traditional - handcuffs a available in a given instance, plastic cuffs – zip-ties – are used [6]. Handcuffs are not intended to be a long-term restraining device as they can be extremely uncomfortable and could potentially result in injury to the subject [7]; therefore, regardless of the reason cuffs are deployed, the design should be such that it minimizes the risk to all persons involved. The time that it takes for handcuffs to be applied and the nature of the application is important to prevent escalation of a given situation and ensure the safety of all involved parties. The comparison of different handcuff designs in a controlled setting can provide important insights into how different design features may impact: 1) injury risk of a person having handcuffs applied to them, and 2) the time it takes for the handcuffs to be applied.

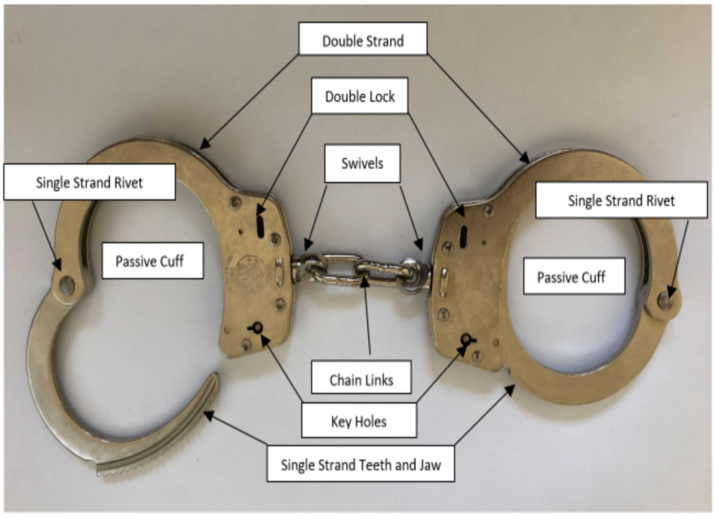

Figure 1: An overview of the Single Pair of Traditional SW M100-1 handcuffs and its components.

Both the style of handcuff and application technique can result in pain or discomfort for the person-in-distress when applied incorrectly [1]. Law enforcement departments issue handcuffs and train their officers to use them properly. However, there are many documented instances where traditional handcuffs types (chain-linked and hinged) have been reported to cause injury at the site of application and increased tightening or aggression from the person applying the cuffs - the cuffer - to the individual being restrained - the cuffee [1, 8]. These injuries include bone fractures and nerve damage to tissue in the surrounding region of handcuff application [1, 9].

Handcuff injuries to the upper extremity go beyond the site of application. Though this is not widely studied scientific literature, there are ample reported instances of shoulder injury arising from - handcuff applications that have made their way into the judicial system in the United States [10, 11, 12]. These cases clearly identify that persons-in-distress can undergo severe shoulder injury during the cuffing process. These injuries can be both neurological and/or orthopedic in nature. Customarily, cuffers are trained to put the cuffee in a posture such that they are flexed at the hips with upper arm internally rotated and extended, the wrists flexed, and the thumbs pointing upward, resulting in a position that would allow for little force generation by the cuffee as they are near their end-range of motion [6]. This position, however, also places the shoulder joint in a position that is more susceptible to injury [13, 14], and in some cases injury can occur even when the person-in-distress notifies the officer of a preexisting condition [11].

The shoulder joint is a delicate structure that is prone to both neurological and orthopedic injuries [13, 15, 16]. Orthopedic injuries to the shoulder joint and surrounding tissues can arise from a multitude of mechanisms including alignment abnormalities, strength and power deficits, and decreased extensibility of the pectoralis minor and posterior shoulder musculature [13], and can occur from a single traumatic incident [16] or overuse [13]. Neurological injuries to the brachial plexus can result from either stretching or compression of the nerve tissue [17]. The application of handcuffs to the person-in-distress is not without risk to that individual as their hands are typically restrained behind their back with their arms extended, adducted, and internally rotated relative to the torso [6]. The combination of these movement patterns along with the flexed h-ip posture places the shoulder joint in positions where shoulder dislocation or rotator cuff injuries can occur [13, 14], as well as nerve damage that has a detrimental impact on bicep tendon reflex, bicep power generation capabilities, and paranes-thesia to C6 dermatome [18].

Handcuff design and the procedures associated with applying them may result in different kinetics and kinematics of the shoulder; with some designs potentially requiring less torque to be applied to the shoulder during application and re-duced activity of the muscles around the shoulder. A new hand-cuff design (Figure 2) has arisen that aims to lower injury risk for the person having the handcuffs applied to them (cuffee), while reducing time of application for the person applying the handcuffs (cuffer). The purpose of this study was to evaluate if SpiderCuff (SC) – a new product with a retractable Kevlar cord joining the bracelets – and a Smith Wesson M-100 linked-chain handcuff (TRAD) (see handcuffs in Appendix A) differ in met-rics that relate to factors that may reduce injury in the cuffee and improve control for the cuffer.

2 Materials and Methods

2.1 Participants

A total of 11 active law enforcement officers, trainers, and trainees between the ages of 18 and 60 were recruited to com-plete 2 visits at the Center for Human Health and Performance at the University of Massachusetts Amherst. One law enforce-ment officer dropped out of the study and did not complete the second visit due to the disruption of the study by the COVID-19 pandemic. Prior to participation, we obtained written informed consent from all participants after informing the of all procedures, potential risks and benefits associated with participation in the study as approved by the University Institutional Review Board for Human Subjects Research.

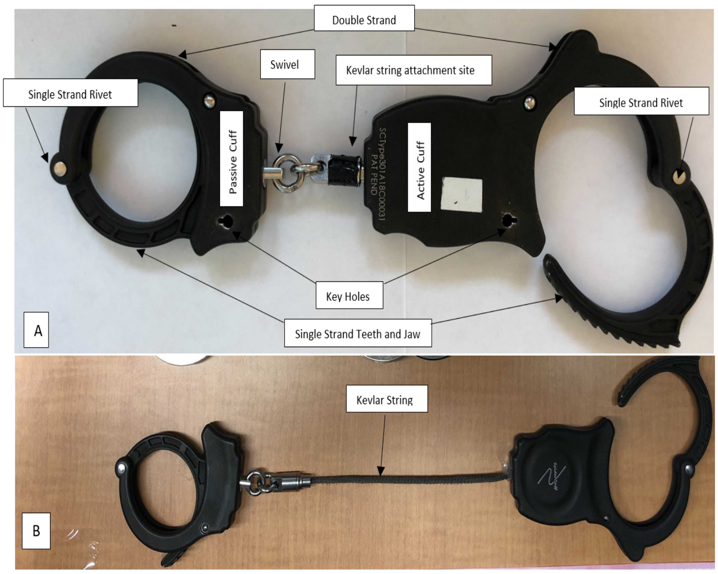

Figure 2: An overview of a new handcuff design by Spider-Cuff Inc. A) Single-pair SC handcuff in its retracted form, B) Single-pair SC handcuff in its extended form.

2.2 Experimental Setup

In both visits, we evaluated four handcuff configurations: a single pair of TRAD, a linked pair of TRADs, a single pair of SC in its retracted form, and a single pair of SC in its extended form (Appendix A).

2.3 Protocol 1

During the first visit, participants applied handucffs to an experimental apparatus six times each for four different cuff con-figurations at two different fixed speeds (30 degrees/second, and 45 degrees/second), for a total of 48 applications. The experimental apparatus consisted of a stationary rig with an at-tached, custom 3D-printed 'arm' secured in a fixed position to simulate an individual's arm being behind the back (Figure 3). The other 'arm' was affixed to a Biodex system 4 Pro dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA) which sampled torque, position, and velocity at 100Hz. The order in which the participant applied each configuration of cuffs was randomized, but the order of application speed was not, with the 30 degrees/second always coming prior to 45 degrees/second. Participants were allowed ample time to familiarize themselves with the equipment prior to testing. All six trials for each cuff configuration were were c-ompleted before moving on to another configuration (Appendix B.1). Instructions for the experiment were consistent across trials, while the specific operation of each cuff type/configuration depended on the condition tested. Prior to each trial, participants stood four feet away from the dynamometer apparatus. All trials were initiated by a 'Ready. . . Go' signal from research staff. Cuffs were applied to the dynamometer arm prior to being attached to the fixed arm to capture all the torque that is applied during the ap-plication of the cuffs. Handcuff application procedures for each handcuff configuration described in the supplemental material (Appednix B.2).

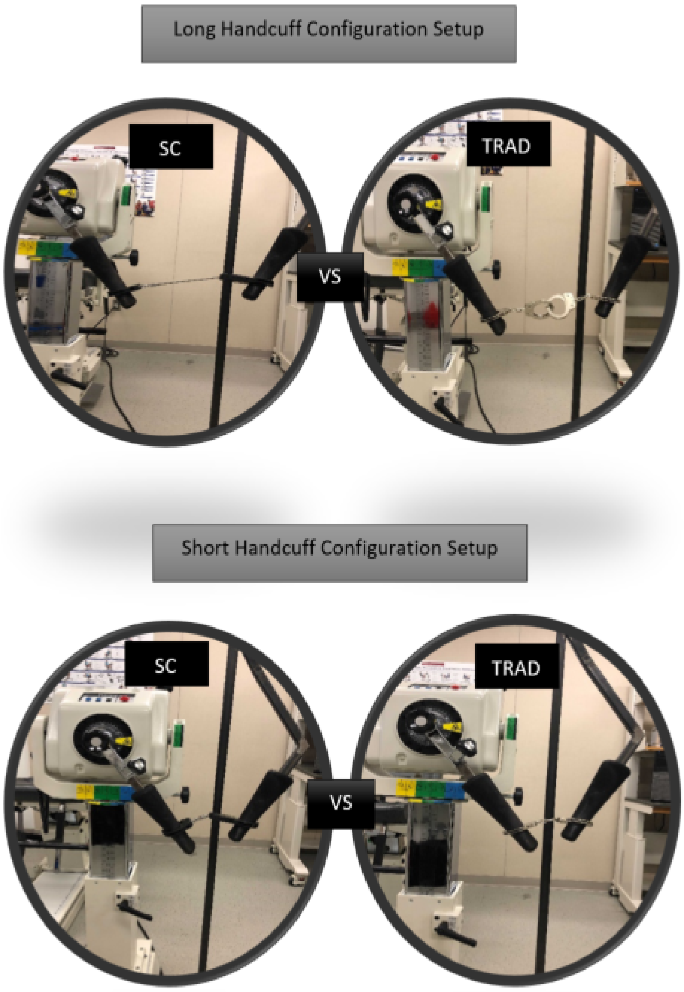

Figure 3: Handcuff Configuration Setups for the dynamometer protocol. The distance between the bracelets of TRAD handcuffs was used to standardize the distance for short- and long- handcuff configuration setups, respectively.

a) The Long Handcuff Configuration Setup with a distance of 32cm between handcuff application sites on the 3D printed arms when cuffs are applied, and b) The Short Handcuff Configuration Setup with a distance of 14cm between handcuff application sites on the 3D printed arms when cuffs are applied. These distances were chosen based on the distance between bracelets of TRAD handcuffs in the short- and long-configurations, respectively, to simulate the effects of different handcuff configurations.

2.4 Protocol 2

During the second visit, pairs of participants applied handcuffs to each other six times for each handcuff configuration. A 9-camera infrared motion capture system (Qualisys, Göteborg Sweden) with a collection frequency of 200 Hz was used to collect shoulder joint kinematics. Bilateral surface EMG activity of the anterior deltoid, posterior deltoid, and pectoralis major muscles was collected at 1926 Hz by Delsys Trigno Electromyography (EMG) sensors (Delsys Inc., Natick, MA, USA). Qualisys Track Manager Software was used to capture and synchronize all data streams. Instructions for the experiment were consistent across trials, while the specific operation of each cuff type/configuration depended on the condition being tested (Appendix B.3).

Bilateral kinematics of the cuffee's upper extremity were measured from calibration markers placed on the forearm: radial and ulnar styloid processes, lateral and medial humeral epicondyles; upper arm: medial and lateral humeral epicondyles, the greater and lesser tuberosity of the humerus, and lateral shoulder to compute shoulder joint center; and torso: acromioclavicular and iliac crest. Segmental motion was tracked from four-marker rigid clusters placed on the torso, upper arm and forearm. A static calibration was done prior to the beginning of all handcuff recordings and was used to create participant-specific kinematic models.

Cuffers were outfitted with a duty belt and handcuff holsters and stood six feet behind the cuffee. During each trial the cuffer removed the cuffs from the duty belt, approached the cuffee, applied the cuffs to the cuffee, and returned to the starting point. The cuffee was instructed not to resist the cuff application, to bend at the hips, and to place their arms behind their back with thumbs pointing upwards to simulate a field encounter in which an officer might have to restrain an individual. These standardized practices are intended to minimize injury risks to all parties involved and were adopted in this study as they simulate a real-world situation when deploying handcuffs peacefully. Six trials were performed in each handcuff configuration to assess kinematic and muscle activation variables.

2.5 Data Processing

A custom MatLab (R2019B) program was used to analyze the dynamometer data. A centered moving average with a 100ms window was used to smooth the signal. Peak Torque (Nm) was quantified as the maximum value of the torque signal during the handcuffing p eriod. Total Impulse (Nm*s) was quantified as the integral of torque with respect to time during which the handcuffs are being applied. Visual 3D (C-motion, Germantown, MD) was used to compute 3D joint kinematics of the shoulder. Kinematic data were interpolated using a least-squared fit of third order polynomial with three-data point fitting and maximum gap of 10 frames. Kinematic data were low-pass filtered using a fourth-order Butterworth filter with cut-off frequency of 8 Hz. A right-hand rule with a cardian rotation sequence (y-x-z) was used for 3D angular computations, where x, y, z represent the sagittal, frontal and transverse planes, respectively. Shoulder angles and angular velocity were expressed in the arm's coordinate system where adduction and abduction are +/-, respectively. EMG signals were filtered u sing a f ourth-order Butterworth band-pass filter with high- and low-pass cut-off frequencies of 28 Hz and 500 Hz, respectively; and the Root Means Square (RMS) signal was averaged over 100 ms window to derive individual muscle EMG signals. Kinematic and EMG variables were evaluated during the handcuffing p e riod, i . e. from first contact of cuffer to the cuffee to when the cuffer removed their hands from the cuffee. For all handcuff configurations, times were recorded from the start of movement of the cuffer toward the cuffee to when the cuffer removed their hands from the cuffee.

To assess the impact of different handcuff configurations on shoulder kinematics we examined Net Shoulder ROM (°) quantified as the differences between maximum and minimum adduction/abduction angles, and Peak Shoulder Adduction Velocity (°*S-1) quantified as the maximum velocity values within the shoulder range of motion time sequmence. To assess the impact of different handcuff configurations on shoulder activation we examined Peak Net EMG (μV) quantified as the average maximum values of summated bilateral shoulder EMG activity during the handcuffing period with respect to a given handcuff configuration; Net EMG (V) quantified as the average sum of bilateral shoulder EMG activity during ROM time sequence with respect to a given handcuff configuration; Net EMG at peak adduction velocity (μV) quantified as the average of bilateral shoulder peaks derived from the sum of EMG activity at the instance of peak adduction velocity for a given handcuff configuration. Additionally we measured Time of Application (s) as the time elapsed from start to end of handcuff procedure. Due to difficulties with capturing the marker data we excluded a range of trials when appreciable marker dropout occurred.

2.6 Statistical Analysis

Outcome measures for Protocol 1 were evaluated on nine of 11 datasets collected; two participants' data were excluded: one withdrew from the experiment due to a 5-month suspension in the data collection due to COVID-19 and the other was excluded because of data quality issues that occurred during collection. The outcome measures from Protocol 1 were: peak torque (Nm) and total impulse (Nm*s). Data from 9 of 10 participants who competed Protocol 2 were used in the analysis of Protocol 2; one participant was excluded because of a technical issue during data acquisition that impacted data quality. Protocol 2 outcome measures include shoulder ROM (°), Peak Shoulder Adduction Velocity (°*s-1), Net EMG (V), Peak Net EMG (μV), Net EMG at peak adduction velocity (μV), and the time-of-application (s). Each subject's multiple trials from each handcuff configuration were averaged to create individual subject means for all outcome measures; the average and standard deviation from all participants for each handcuff configuration were used to calculate the Effect Size differences (Cohen's d) for each outcome measure to evaluate the differences between TRAD and SC in the short and long configurations. Additionally, for Protocol 1, each of the two isovelocity conditions were evaluated separately. Standard Cohen's d effect-size ranges were Ased Ao Aetermine Ahe magnitude of Affect: negligible < 0.2, Amall = 0.2-0.49; moderate = 0.5-0.79; large ≥ 0.8 [19]. A negative A Andicates Ahat Ahe mean Aalue Aor SC Aas greater than TRAD, while positive values indicate that the mean of TRAD was greater than SC. Percent difference between SC and TRAD handcuffs as the absolute value of the differences over the mean times 100 for each variable in both testing protocols and con-figurations.

3 Results

3.1 Visit 1 – Dynamometer

During the first visit, a range of effect-size differences were observed in average peak application torque and average total impulse of application between TRAD handcuffs and SC across speed and cuff-configuration comparisons. Mean and Standard deviations for long- and short- handcuff configurations dynamometer variables are in Table 1. Effect sizes for both long- and short- handcuff configurations are presented in Figure 4.

Table 1: Means and Standard Deviation for dynamometer variables for both long- and short-handcuff configurations.

Short Configuration		
Dynamometer Visit Variables	*Spidercuff*	Traditional cuff
Peak Torque (Nm) 30 deg/sec	3.8±1.4	5.8 ±2.4
Total Impulse (Nm*s) 30 deg/sec	1.37±0.57	2.73±1.4
Peak Torque (Nm) 45 deg/sec	5.6±2.9	9.2±7.2
Total Impulse (Nm*s) 45 deg/sec	1.4±0.8	3.5±2.7
Long Configuration		
Dynamometer Visit Variables	*Spidercuff*	*Traditional cuff*
Peak Torque (Nm) 30 deg/sec	3.8±2.0	6.4 ±4.5
Total Impulse (Nm*s) 30 deg/sec	0.5±0.2	0.6 ±0.2
Peak Torque (Nm) 45 deg/sec	5.0 ±3.6	7.0 ±6.4
Total Impulse (Nm*s) 45 deg/sec	0.6 ±0.2	0.6 ±0.2

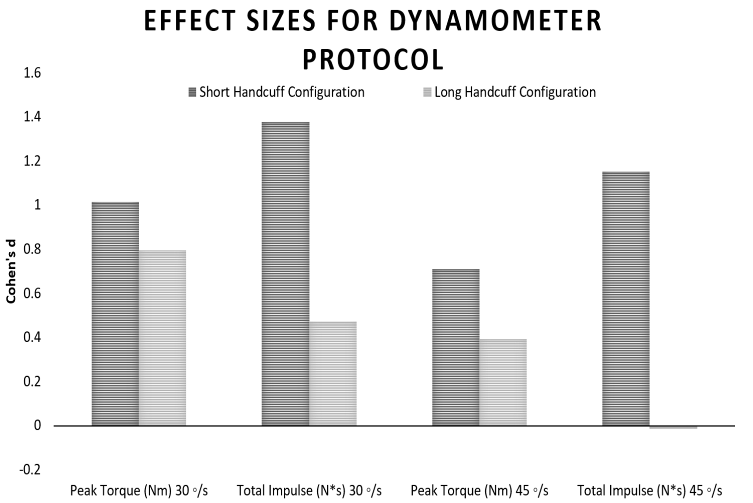

Figure 4: Effect Size differences for dynamometer vari-ables for both long- and short-handcuff configurations. Effect sizes in the positive direction represent a lower mean values observed in SC compared to TRAD. Effect sizes in the negative direction represent a higher mean values ob-served in SC comparted to TRAD.

3.2 Peak Torque

For the 30 degrees/second trials, a large effect-size was observed for peak torque between the SC and TRAD in the short-handcuff configuration (d=1.01) and a moderate effect-size difference in the in the long-handcuff configuration (d =0.79); in both cases SC displayed lower average peak torque than the TRAD by 41% and 51%, respectively. Similarly, in the 45 degrees/second trials, SC exhibited lower average torque than TRAD with moderate effect-size difference (d=0.71) observed in the short-handcuff configuration and a small effect-size difference (d=0.39) in the long-handcuff configuration; i n both cases SC displayed lower average peak torque than the TRAD by 49% and 33%, respectively. For both testing velocities and handcuff configurations, it appears that SC outperformed TRAD cuff as we observed lower average peak torque in Table 1.

3.3 Impulse

For the 30 degrees/second trials, a large effect-size was ob-served for total impulse (Nm/second) between SC and TRAD cuffs for the short-handcuff configuration (d = 1.38) and a small effect size difference for the long- handcuff configuration (d=0.47); in both cases SC displayed lower average impulse than the TRAD with 66% and 18%, respectively. For the 45 degrees/second trials, a large effect-size difference (d=1.15) was observed only in the short-handcuff configurations with the SC displaying lower average impulse; while a negligible effect-size difference (d=-0.01) was observed in the long- handcuff configuration by 86% and 0 % , respectively. For both testing velocities and short-handcuff configurations, it appears that SC outperformed TRAD cuff as we observed lower Total Impulse on average. However, for the long-handcuff configuration at both testing velocities neither cuff type is superior compared to the other as shown in Table 1.

3.4 Visit 2

During the second visit, a range of effect-size differences were observed between TRAD and SC across the cuff-configuration comparisons for the shoulder kinematics, net muscle activation, and Time-of-Application. Means and Standard deviations for long- and short- handcuff configurations are shown in Table 2. Effect sizes for a given configuration type are presented in Figure 5.

Table 2: Means and Standard Deviation for motion capture variables for both long- and short- handcuff configurations.

Short Configuration		
Motion Capture Variables	*Spidercuff*	*Traditional cuff*
Net Shoulder ROM (deg)	14.4±2.4	18.2±3.9
Peak Shoulder Adduction Velocity (deg/sec)	28.0 ±13.4	29.5 ±17.9
Peak Net EMG (μV)	242 ±97	242 ±114
Net EMG (V)	3.9 ±6.8	4.5 ±6.6
Net EMG at peak adduction velocity (μV)	215±96	190±103
Time of Application (s)	9.1±1.9	8.4±2.0
Long Configuration		
Net Shoulder ROM (deg)	17.9 ±4.7	17.1 ±5.4
Peak Shoulder Adduction Velocity (deg/sec)	25.0±11.0	28.6 ±11.9
Peak Net EMG (μV)	278 ±117	283±157
Net EMG (V)	4.5 ±6.8	4.4±8.4
Net EMG at peak adduction velocity (μV)	266 ±114	203 ±102
Time of Application (s)	9.9 ±1.8	13.2 ±1.8

3.5 Kinematics

A large effect-size (d=1.21) was seen in the net (combined Left Right) shoulder adduction ROM in the short-handcuff condi-tion, with the SC requiring less shoulder ROM to restraint by 23% . A negligible effect-size difference (d=-0.16) in the net shoulder ROM was observed in the long-handcuff configura-tion, with both SC and TRAD required similar shoulder ROM to restraint with 4.57% difference. Meaningful

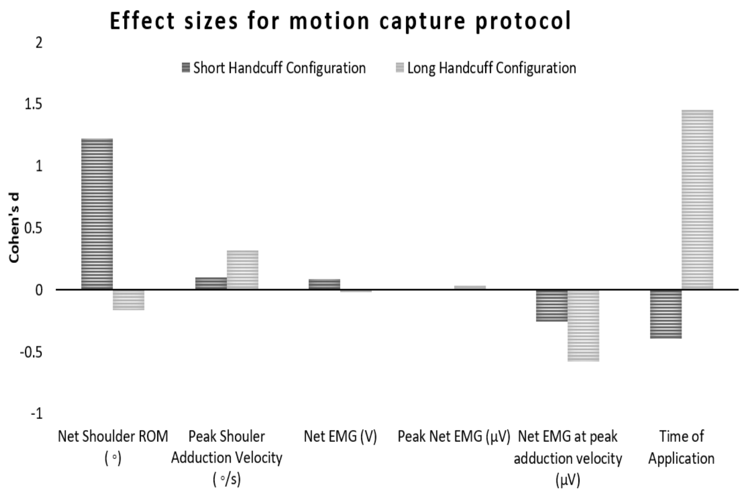

Figure 5: Effect Size differences for motion capture vari-ables for both long- and short-handcuff configurations. Ef-fect sizes in the positive direction represent a lower mean values observed in SC compared to TRAD. Effect sizes in the negative direction represent a higher mean values ob-served in SC compared to TRAD.

differences are evident in the kinematic variables, with SC outperforming TRAD cuffs in shoulder ROM required to restraint an individ-ual when using cuffs in the short-configuration. Peak veloc-ity comparisons indicated that there were negligible and small effect-size differences between SC and TRAD in the short-handcuff configuration (d=0.1) and long- handcuff configuration (d=0.32), respectively. There is no apparent difference in peak velocity when using cuffs in the short- configuration (5.2% difference), but it appears that SC slightly outperforms TRAD in the long-handcuff configuration (13% difference), when evaluating Peak Shoulder Adduction Velocity as shown in Table 1.

3.6 Muscle Activation

Negligible effect-size difference between SC and TRAD were observed between the peak net muscle activation in both the short- (d=0.005) and long- (d=0.03) configuration comparisons. The net muscle activation at peak velocity revealed small and moderate effect size differences in the short- (d=-0.26) and long- (d=-0.58) cuff comparisons, respectively, with the TRAD demonstrating less muscle activity in both instances. Negligi-ble differences in net muscle activation were observed in both the short- (d=0.08) and long- (d=-0.02) cuff conditions. Slight differences in net muscle activation at peak velocity observed in favor of TRAD handcuffs, where SC stimulates muscle ac-tivation to a greater magnitude at the instance of peak velocity during handcuff application for both short- and long- handcuff configurations by 12% and 27%, respectively.

3.7 Time of Application

A small effect-size was observed (d=-0.39) in time of hand-cuff application in the short configuration; while a large effect-size difference (d=1.45) was observed in the long configuration, with the SC taking less time to apply. Our results indicate that SC handcuffs are applied 29% faster than TRAD in the long-configurations, but when assessing the short-configurations TRAD are applied 8% faster than SC handcuffs.

4 Discussion

We conducted a series of two experiments to investigate the differences between SC and TRAD handcuff designs on factors salient to the ergonomics and safety of both the cuffer and cuffee, with a primary focus on the factors that would impact the cuffees' shoulder joint. The experimental approach in both experiments aimed to provide data in as ecological a setting as possible while also controlling for factors that could confound the findings. For both the dynamometer and cuffer/cuffee applications of the cuffs, we adopted configurations and postures that reflect the typical approach of restraining an individual: hands behind the back while the arm is adducted relative to the torso [6]. While this is the standard position, it is known that this position places the shoulder joint and surrounding tissues in a position that can increase the prevalence of shoulder injury [13, 14]. Across both experiments, we found that SC generally outperformed or was equivalent to TRAD handcuffs in factors that could reduce the likelihood of injury to a cuffee, while also finding mixed results in the time-of-application, which could impact the cuffer. In general, this experiment revealed that when differences arose between SC and the TRAD, SC was able to be applied more quickly, required less shoulder adduction, and lower peak muscle activation.

In the simulation experiment, where trained officers placed the handcuffs on 3D printed arms that were mounted to a static rig and a dynamometer arm; we found that SCs are applied with lower peak torque and total impulse compared to TRAD cuffs in both short- and long-handcuff configurations at both 30 degrees/second and 45 degrees/second with the exception of the long-configuration at 45 degrees/second where SC and TRAD had the same average impulse of application. Reductions in peak torque and total impulse in this simulation cannot be solely attributed to the shoulder because other segments of the arms move such as the elbow and wrist joints when cuffs are typically applied in a real-world encounter, but do provide insight to what the net torque applied to the upper extremities looks like during cuffing. The typical pose that officers are trained to utilize in the field places the elbow and wrist at terminal end range with little to no room allowed for additional motion by these joints. This ultimately results in most of the torque and motion occurring at the shoulder during adduction/extension of the arm in a manner known to place the shoulder at risk for injury [13, 18, 20]. Although shoulder internal rotation and extension were not explored in this study, it is important to note that in addition to motion limitations at the elbow and wrist the shoulder is internally rotated and extended also limiting allowed motion at the shoulder in those planes of motion further restricting the shoulder prior to adduction of the arm when cuffs are applied. While there is lack of reporting of epidemiological prevalence of police causing this type of injury in the academic literature, there are numerous cases that have been brought to court that identify serious shoulder injury as a result of handcuffs being placed on a person in distress [11, 12].

In Protocol 2, in which trained officers placed the handcuffs on each other, we did not observe meaningful differences between TRAD and SC for Peak Shoulder Adduction Velocity. In the short-handcuff configuration, the Short-SC configuration required less shoulder adduction ROM than the single TRAD handcuff. The reduction in adduction ROM indicates that the arm is in a less extreme posture which places it at a lower risk of injury for a cuffee with shoulder mobility impairments given the known increased risk of injury that occurs near the end ROM of the shoulder [21, 22, 23]. For ROM when using a long-handcuff configuration, a negligible difference not even rising to a low effect suggest that neither cuff reduces risk of injury of shoulder tissue. This lack of a difference was not surprising given that in our population the cuffee's wrists were not drawn together nearly as much in this long- configuration; this may be different if the cuffs were applied to a person of large girth, which was not the case in our cohort. Reducing the ROM requirement to apply the handcuffs may place the shoulder at lesser risk of injury, especially when this con-tributes to keeping the joint further from terminal joint motion [21]. Ultimately, minimizing the need for end range motion during cuffing is likely favorable in terms of preventing an in-jury that may occur because of adduction of the arm. Peak Velocity during handcuffing revealed a negligible and small effect size in long- and short-handcuff configurations, respectively, with little to no difference in short-handcuff configurations and a slightly lower (2.6 degrees/second) peak velocity values with SC long-configuration than TRAD. Despite the slightly lower peak velocity in favor of SC long- handcuff configuration, these differences are small enough that it is unclear at this time if they would constitute a clinically meaningful difference in in-jury risk to the shoulder between the different handcuff types. This negligible difference in peak velocity is likely due to the fact that law enforcement personnel use their dominant hand to apply the cuff while holding the wrist of the detainee using the non-dominant hand, thus peak shoulder adduction veloci-ties are likely a reflection of the off-hand pulling the detainees' arm towards the midline of the body.

To gain an insight on the resistive joint torques across the shoulder, we measured EMG activity as surrogate for joint torque in visit 2; based on the linear relationship between EMG activities, motor unit recruitment, and forces exerted by muscles to skeletal structures [24, 25, 26]. Paired with our instructions not to resist cuffing, it is reasonable to assign EMG activity to changes in muscle length associated with joint stabilizing torques [27, 28, 29, 30]. Negligible differences in total net muscle activation between TRAD and SC across both cuffing configurations suggest that neither cuff type results in inherently lower resistive muscle activity in a compliant cuffee. However, the higher net EMG at peak adduction velocity with the SC handcuffs are indicative, while small to moderate in effect, may be more reflective of the EMG being captured in a smaller amount of time and across a lower range of motion then being indicative of a substantially stronger resistive force. This is supported by the lack of difference in peak net EMG observed.

The time it takes a cuffer to apply cuffs can directly influence the safety of all involved in the situation. The time of application was examined to identify differences in the human factors related to the deployment of the different handcuff types by the cuffer. We observed a strong effect-size difference between the cuffs in the long-cuff configuration such that SC was 28% faster to deploy than TRAD. A low-to-moderate effect was observed in the short configuration where the TRAD cuff was faster to deploy. The pattern of results was not sur-prising given the steps necessary to deploy each cuff type in the respective configurations. In the short-configuration the SC has the extra step of extending the cord to secure both bracelets before drawing the hands together. This extra step, which on average took less than 1s, corresponded with a lower adduction ROM and peak velocity in the cuffee, both of which should be beneficial to the cuffee. Likewise the large difference observed in the long-configuration was not surprising as the cuffer did not have to join two pairs of TRAD prior to applying them to the cuffee.

5 Conclusion

Differences between SC and TRAD handcuffs revealed that while there were mixed findings on which handcuff performed 'better' overall, there was a consistent pattern that when SC out-performed TRAD it was by a larger margin than when TRAD outperformed SC. In many cases the results of the SC in the short-configuration - a configuration that would be thought to elicit higher torques and larger ranges of motion compared to the long-configuration – were even lower than the TRAD in the long-configuration. This suggests that the SC may result in lower shoulder injury risk than TRAD, though this would need to be confirmed from epidemiological studies. While we made every effort to create laboratory tasks that would be reflective of real-world conditions, we recognize that there are multiple factors that could influence the risks to both cuffer and cuffee.

6 Funding

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7 Conflicts of Interest

None of the authors have conflicts of interest relevant to the content of this article.

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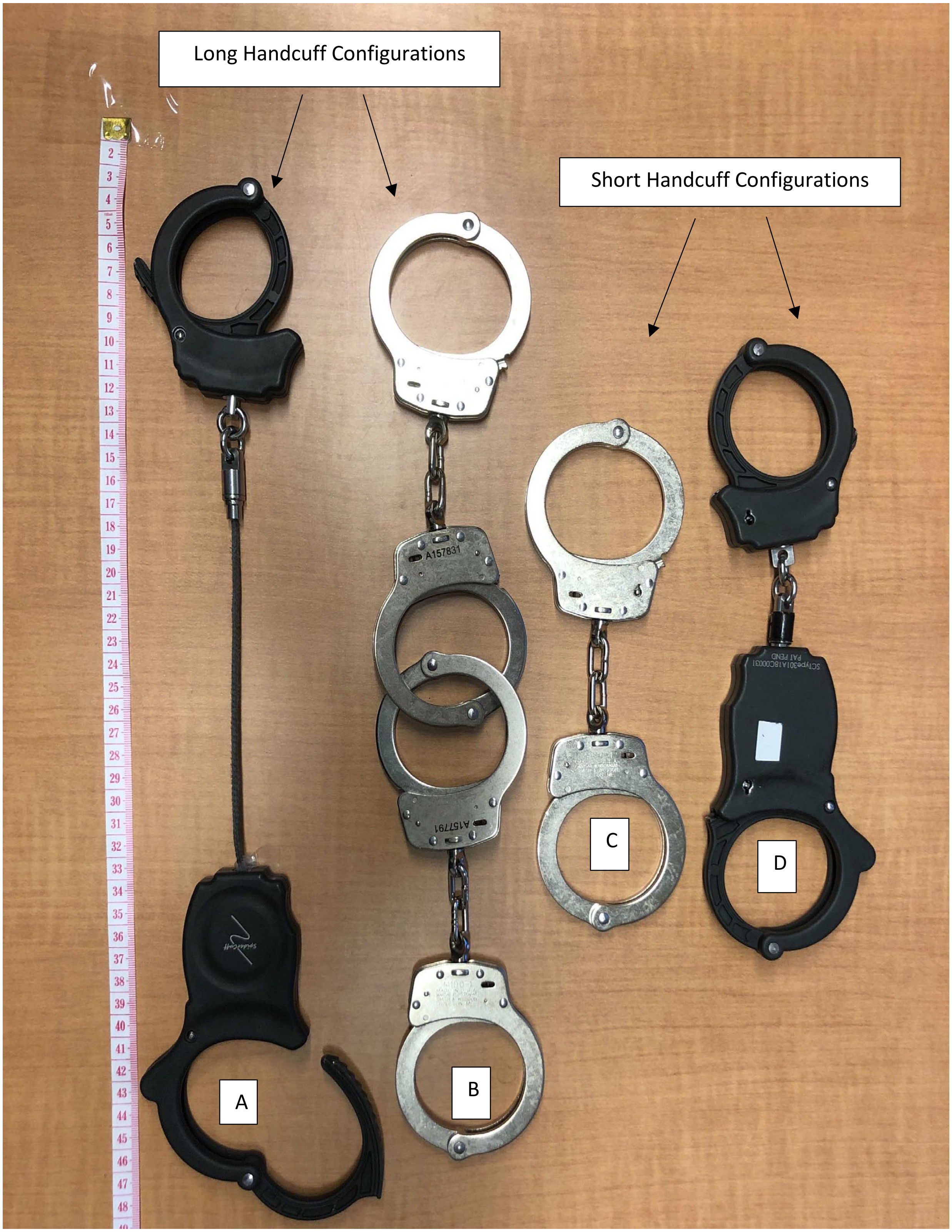
Appendix A



All handcuff configurations used by each officer included in the study. A) Single-Pair SC in its extended form. B) Double-linked pairs of TRAD, C) Single-pair of TRAD, D) Single-pair SC in its retracted form.

Appendix B

Table 1*:* Handcuff configurations and speeds applied to the dynamometer arm in protocol 1.

	Configuration	**30 °/s**	**45 °/s**
Short Handcuff Configurations	Single pair of traditional cuffs	✓	✓
	Retracted SpiderCuffs	✓	✓
Long Handcuff Configurations	Two linked pairs of traditional cuffs	✓	✓
	Extended SpiderCuffs	✓	✓

Table 2: Handcuff application procedures for each handcuff configuration during protocol 1.

Short Handcuff Configurations	**Traditional Cuffs - Single Cuffs**
	1. Apply cuff to 'wrist' of the dynamometer arm. 2. Apply remaining cuff to wrist of fixed arm. 3. Bring wrists together. 4. The trial is complete when the officer releases the cuffs.
	SpiderCuff – Retracted
	1. Apply passive cuff to of the dynamometer arm. 2. Extend active cuff of SpiderCuff and apply it to the wrist of the fixed arm. 3. Bring wrists together such that the SpiderCuff cord is completely retracted. 4. The trial is complete when the officer releases the cuffs.
Long Handcuff Configurations	**Traditional Cuffs - Double Cuffs**
	1. Starting with a two linked pair of handcuffs, apply cuff to 'wrist' of the dynamometer arm. 2. Apply remaining cuff to wrist of fixed arm. The trial is complete when the officer releases the cuffs.
	SpiderCuff – Extended
	1. Apply passive cuff to of the dynamometer arm. 2. Extend active cuff of SpiderCuff and apply it to the wrist of the fixed arm. 3. Leave the SpiderCuff in the extended position. 4. The trial is complete when the officer releases the cuffs.

Appendix B

Table 3: Participant instructions during protocol 2.

Configuration Type	Traditional Cuffs - Single Cuffs
Short Handcuff Configurations	1. Research staff 'GO' 2. Remove cuff from holster. 3. Apply cuff to wrist of person in crisis.
	4. Apply cuff to other wrist of person in crisis. 5. Check for tightness, double lock. 6. The trial is complete when the cuffer lets go of the cuffs.
	SpiderCuff – Retracted
	1. Research staff 'GO'. 2. Remove cuffs from holster. 3. Apply passive cuff to wrist of participant. 4. Extend active cuff of SpiderCuff and apply it to 'other wrist' of participant. 5. Check for tightness, double lock. 6. Bring the wrists together such that the SpiderCuff cord is retracted completely. 7. The trial is complete when the cuffer lets go of the cuffs.
Long Handcuff Configurations	**Traditional - Double Cuffs**
	1. Research staff 'GO'. 2. Remove cuffs from holster. 3. Apply cuff to wrist of cuffee 4. Apply cuff to other wrist of cuffee 5. Check for tightness, double lock cuffs. 6. The trial is complete when the cuffer lets go of the cuffs.
	SpiderCuff Extended
	1. Research staff 'GO'. 2. Remove cuffs from holster. 3. Apply passive cuff to wrist of participant. 4. Extend active cuff of SpiderCuff and apply it to 'other wrist' of participant. 5. Check for tightness, double lock. 6. Leave the SpiderCuff in the extended position. 7. The trial is complete when the cuffer lets go of the cuffs.