Comparison of infant car seat grip orientations and lift strategies

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ABSTRACT

The rear-facing Infant Car Seat (ICS) is designed to meet federal requirements for transporting children less than 1 year old. Typical use includes transfer in and out of a vehicle, which is shown to be a difficult lift. Despite the frequency of this lift, manufacturers provide little guidance for users. Review of relevant literature suggested an ICS featuring an angled handle, promoting a neutral wrist posture, would increase grip stability and decrease lifting effort. Popular press suggested a foot-in-car stance for the ICS lift would do the same. An experiment was conducted in which wrist deviations from neutral posture were recorded along with lifting muscle activation levels (multiple flexor muscles and biceps brachii) and overall perceived exertion for straight versus a new bent handle design and conventional stance versus foot-in-car. Foot position was examined to test the recommendations in the popular press. Surprisingly, wrist deviation was not significantly affected by the new bent handle design (due to compensatory behavior with the straight handle) but was related to foot placement ($p = 0.04$). Results revealed the bent handle to significantly reduce flexor activation compared with the straight handle ($p = 0.0003$); however, the level of biceps activation increased. Biceps activation also significantly increased for foot-in-car stance ($p = 0.035$) but not flexor activation. In general, the bent handle enabled the user to lift the ICS with a steadier grip and less effort.

1. Introduction

All 50 US states require the use of a child restraint when transporting a child in a motor vehicle. For example, the state of North Carolina requires, "every driver who is transporting one or more passengers of less than 16 years of age shall have all such passengers properly secured in a child passenger restraint system or seat belt which meets federal standards applicable at the time of its manufacture" (NC Child Passenger Safety Law, GS 20-137.1). The rear-facing Infant Car Seat (ICS) is designed to meet federal and state legal requirements for transporting children less than 1 year old. The primary use of an ICS is to protect an infant in the event of a crash. However, since they are used during the first year when a child cannot move effectively on its own they also often serve as a form of transport for the infant over short distances. Many ICSs can be attached to a stroller to create a "travel system" that integrates the seat with the stroller. Therefore, use of the ICS as a travel system entails transfer of the seat between the vehicle and the stroller.

Removing an ICS from a car, requires: (1) rotating the carrying handle from a locked position to a carrying position; (2) unlocking the ICS from its secure base; and (3) lifting the ICS from the car and placing it in a stroller. These steps are performed while the user bends down to see into the car, takes care to clear their head during entry and exit of the vehicle, leans in the car, and lifts the load offset from the base of support.

A review of ICSs available through a large retailer (Babies R Us, 2010) revealed an average weight of approximately 4.5 kg (without the base) and suitability for protection of an infant up to 13.6 kg (18.1 kg total load). The awkwardness of the posture combined with the weight of the load make the ICS lift a difficult and potentially dangerous task for the user in terms of acute injury. Nevertheless, one survey of lifting tasks performed by mothers showed that the position of the car seat is selected to maximize child's safety and has little to do with user lifting strategy (Griffin and Price, 2000). Despite these issues, ICS manufacturers provide little or no guidance for safe lifting procedures in product manuals.

Articles in the popular press acknowledge the difficulty of lifting an ICS and suggest a symmetrical lifting strategy where two hands are used to grasp the handle simultaneously (Consumer Reports, 2009). They also recommend an alternate posture to make the lift easier, including placing one foot in the car (Consumer Reports, 2009, 2010); however, such methods have not been validated empirically. These same publications also recommend removing the infant from the ICS and leaving the seat in the car due to the

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lifting difficulty. However, parents typically carry the ICS to prevent waking a sleeping baby (Griffin and Price, 2000).

Two major companies, Evenflo and Baby Trend offer alternatives to the traditional "straight" handle. Evenflo patented a handle that is 90° offset from the straight handle position (Fig. 1), but the patent does not mention the reasons for this design (Gibson and Meeker, 2000). Baby Trend patented a triangular-shaped handle that offers multiple hand positions for lifting and carrying the ICS (Fig. 2). The patent claims the handle is "ergonomically shaped;" however, evidence for this assertion was not provided (Sedlack, 2005).

Despite a large body of research devoted to handle design for industrial tasks, research directly relevant to lifting an ICS from an automobile is limited. This is likely because parents are generally responsible for bringing infants into child care facilities, etc. and not child care professionals, who have been the subjects of occupational studies (Sanders and Morse, 2005). Previous studies, such as Griffin and Price (2000) provide subjective data on physical stresses experienced by parents, but no exposure data specific to the ICS. Sanders and Morse (2005) also observed a lack of quantitative data on ergonomic risk factors for parents and performed their own survey of musculoskeletal symptoms and contributing factors. They found 66% of parents experienced some discomfort related to child care with 44% of these persons reporting shoulder, neck, and upper back pain. Lifting the ICS from a vehicle was used as an example of a high risk task by the authors, but it was not included in their survey. Therefore, although Sanders and Morse found high stress lifting combined with a limited awareness of lifting postures contribute to musculoskeletal symptoms, no prior work has identified ICS lifting as an activity directly leading to repetitive stress disorders, such as low back pain or disability. This is expected as ICS removal is a non-repetitive lifting task unlike industrial material handling tasks normally associated with chronic ailments. There is still motivation, however, to examine the handle in terms of maximizing infant safety during transfer from an acute injury (sprain, strain) perspective.

Hand tool design is one area which is related to the handle to arm interface. Literature in this area indicates that hand and forearm alignment influence operator lifting effectiveness and, in fact,
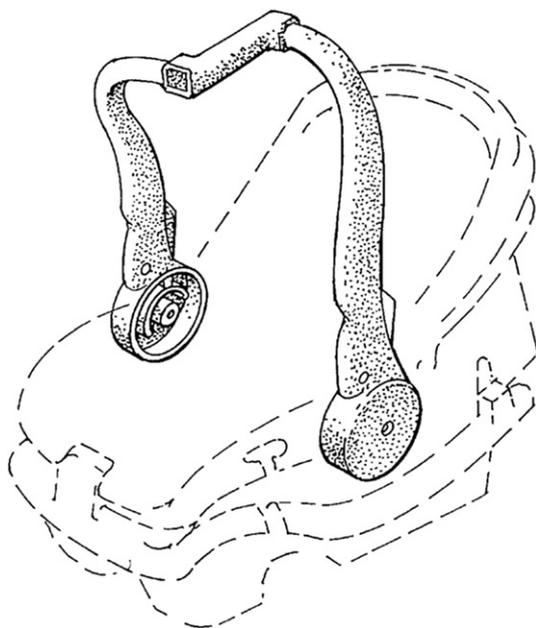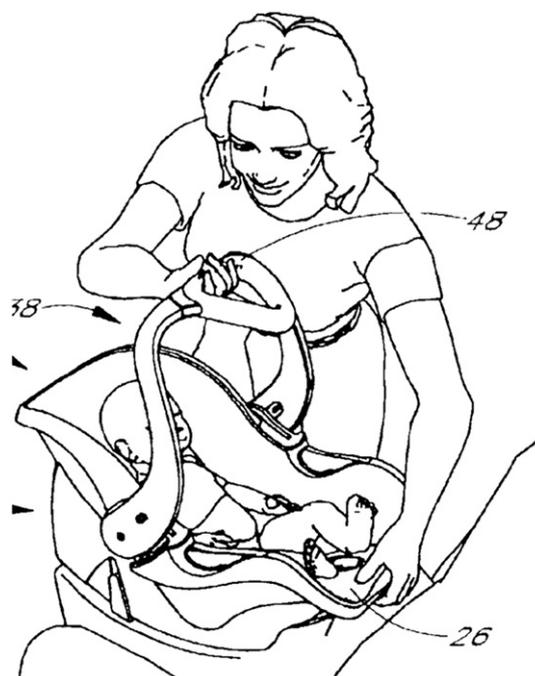

Fig. 2. Baby trend triangle handle (Sedlack, 2005).

suboptimal wrist deviations reduce grip strength, which can also compromise the steadiness of the load (Lewis and Narayan, 1993; Moore et al., 1991). Furthermore, continued exposure to a task requiring a deviated wrist position relative to the forearm can result in "inflammation, chronic pain and possible permanent injury" of the wrist (Lewis and Narayan, 1993).

According to Strasser et al. (1996), tool design that promotes compatible alignment of the hand and arm can reduce physical exertion. In this same study, the team advocated the use of electromyography (EMG) in controlled laboratory settings as an objective measure of physiological costs associated with tool design and use. The use of EMG is also supported by Moore et al. (1991) as an objective measure of musculoskeletal demand during manual tasks with hand tools.

There is also some relevance in prior studies in manual materials handling (MMH) to the ICS handle design. Unfortunately, several characteristics of the ICS lift, such as the unusual body posture, where one hand is held high above the center of the load, and the low lifting frequency are not common to industrial tasks that have generally been examined in the MMH literature, and directly relevant information is limited. In a study measuring hand and arm stresses resulting from various handle positions for a static box holding task, Coury and Drury (1982) noted that if the angle between a box handle and the forearm is not 90°, wrist deviation is necessary to correct the difference. Furthermore, optimal handle design is difficult for lifting tasks because the optimal angle will vary according to the height throughout the lift and as the direction of the load's downward force changes in relation to the forearm position. According to Drury et al. (1985), the optimal handle angle is between a neutral wrist posture and up to 10° of ulnar deviation. Deviations from this range have been shown to be a source of worker discomfort (Coury and Drury, 1982). However, operators may attempt to avoid uncomfortable wrist deviations by loosening their grip, leading to a higher slippage angle and less control of the load. This increases the risk of dropping the load (Drury et al., 1985), which would be a critical outcome in ICS handling. Therefore, if the wrist is not in a neutral posture or deviated 10° or less in the

Fig. 1. Evenflo offset handle (Gibson and Meeker, 2000).

direction of the ulna, the ICS user will be subject to discomfort during lifting and may reduce their grip force and potentially compromise seat and child stability.

In a survey of MMH tasks, Drury (1980) reviewed handle design parameters and observed that criteria for determining handle suitability could be grouped into four categories including: (1) anthropometric data, (2) force/torque production, (3) safety performance and (4) fatigue minimization. The present study was concerned with the first three criteria, including the structure of the body for ensuring a neutral wrist posture in the ICS lift, reduction of muscular effort relative to the load, and ensuring grip stability for lifting safety. Given the difficulty of the ICS lift and the expectation parents will continue to remove seats from automobiles with infants secured inside using postures that prioritize child safety, there is motivation to evaluate alternate handle designs that meet these criteria. In this study we focused on measuring the impact of high exertions in the small muscles of the forearm (flexor) and the biceps brachii (biceps) in ICS lifting to identify loading tradeoffs due to postural changes affected by handle design. We also conducted correlation analyses to determine whether handle design mediated posture position and, consequently the pattern of muscle activity in the upper-extremity. The recommendations based on the MMH and hand tool design literature were considered in the design of an alternative bent handle, oriented for maintaining a neutral wrist posture in removing an ICS from a vehicle. This modification was also expected to reduce the muscle force in handling an ICS. The new handle was compared with the conventional straight handle design in a lab experiment along with comparison of the foot-in-car versus double-foot stance to test the lifting strategy recommended by Consumer Reports.

2. Methods

2.1. Task

The lifting task studied in the experiment involved reaching into a mock-up of a car doorway, lifting an actual ICS from a car seat, and placing it in a chair representing a stroller positioned adjacent to a vehicle. During the task, participants approached the car doorway and placed their feet according to the condition described for that lift. They then reached into the car and placed the left hand on the ICS release button, which allowed the ICS to be lifted from its base. The participants placed the right hand on the rubber grip of the ICS handle and lifted it (underhanded) from the car. They then turned to the right and placed the ICS in the chair to complete the lift. The participants rested between repetitions of the task while the ICS was replaced in the mock car seat and response data were saved.

Previous MMH research has shown that even experienced professionals generally do not agree on optimal lifting methods (Authier and Lortie, 1993). Therefore, the lifting strategy was defined based on a review of current ICS instruction manuals. All ICSs have a handle that arcs over the center of the seat perpendicular to the infant's seated position and a release for the locking mechanism is located beneath the head of the seat. To be consistent with current ICS design, the strategy included lifting with the dominant hand on the handle while balancing the load with the non-dominant hand on the release mechanism.

2.2. Apparatus

The experimental apparatus included a wood and cardboard frame modeled after the driver's side doorway of the back seat of a 2007 Honda Accord, a captain's style seat taken from a minivan and secured on a base, the ICS itself with its base, and a chair representing a stroller to receive the ICS at the end of the lift. The

doorway was built to replicate real-world conditions, limiting participant access to the ICS. The van seat was used to represent actual vehicle seat shape and was mounted on a stable frame constructed to bring the seat to appropriate height for the model. The car doorway frame was modeled based on measurements of the back seat of the actual vehicle. These included the doorway height and width, location of the open door relative to the door frame, location of the van seat relative to the door frame and the height of the van seat's base. The arrangement of the apparatus is shown in Fig. 3.

An existing ICS was modified by removing the original handle and replacing it with straight and angled handles constructed of PVC pipe (of similar strength and durability) that could be easily exchanged during experimental testing (Fig. 4). Both handles had a circumference of 40 mm to be consistent with handle design guidelines for optimizing grip strength (Drury, 1980). The straight handle was considered as the control condition and the handle extended away from the body in the sagittal plane during lifting. The angled handle was the treatment condition and was offset 17-° from the sagittal plane to allow for a neutral wrist position while gripping the handle. This bent handle design is consistent with Bennett's recommendations for handles in which the longitudinal axis of the grip is offset by approximately 15–25° to accommodate the "natural angle of the hand and wrist in a gripping position" (Bennett, 1977). The ICS (carrying a doll), which originally weighed 5 kg, was weighted with an additional 4.5 kg hidden beneath the seat upholstery. This brought the total weight to approximately 9.5 kg.

Muscle activity was recorded using a Run Technologies Myopac® belt-mounted EMG transmitter connected with two pairs of In Vivo Metric® bipolar silver surface electrodes. The Myopac was connected to a DataTranslation receiver/decoder unit using a fiber optic cable, which was in-turn connected to a laptop via USB cable for data analysis using quickDAQ software. Wrist deviations were measured using an electrogoniometer from Thought Technology Ltd. installed with twin axis SG-75 sensors from Biometrics Ltd. designed for use with the wrist. Electrogoniometer data were acquired using Dynamap software.

2.3. Participants

The study's participants included 10 adult females with a mean age of 23.5 years (SD = 2.01). Potential participants who responded to recruiting efforts were screened for right hand dominance, 5th to 20th percentile stature (5′ and 5′2″), previous exposure to ICS use, and previous back injury or pain. The height restriction was set to
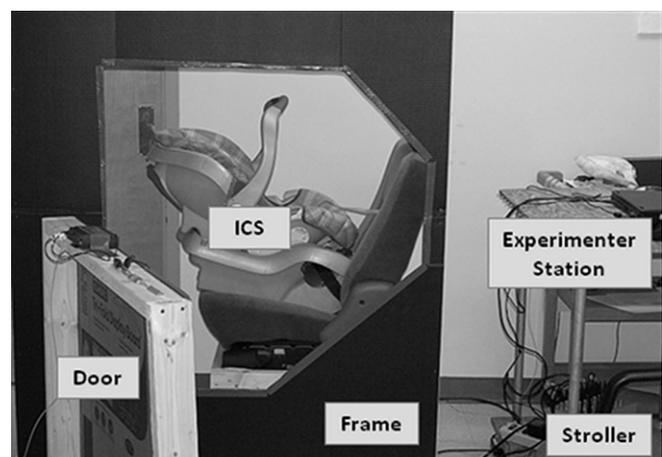

Fig. 3. Experiment setup.

Fig. 4. Straight and angled handle configurations.

reduce variability in lifting posture that would result from bending below the mock doorway ceiling from different heights in order to lift the weight, which was at a static height from the ground. Parents and child care workers were excluded from the study to eliminate persons with previous experience or knowledge of ICS lifting strategies. Inexperienced participants were selected to reduce potential variability introduced by varying lift strategies. Given the likelihood of inconsistent lift strategies among experienced users (Authier and Lortie, 1993), it was expected that novices would follow the manufacturer's lifting guidelines more reliably. Participation was limited to those without a history of lower back injury or pain to prevent inflammation of the condition by repeated lifting. Participants were compensated $10 per hour for the 2 h study, totaling $20.

2.4. Experimental design

Two independent variables (IV) were manipulated in the experiment, including the handle type (straight and angled) and foot placement. Foot placement was either in the car (left foot on a simulated floorboard with the right foot on the ground) or outside with both feet on the ground. The experimental design was a 2 × 2 factorial design with four possible combinations of the two levels of each factor (see Table 1).

Four dependent variables (DV) were recorded during the experiment including: (1) the level of biceps activation; (2) the level of flexor activation; (3) the degree of ulnar wrist deviation from a neutral posture; and (4) the level of perceived exertion in the lift. Biceps and flexor activation were measured using the EMG system (see Fig. 5 for an image of the Run Technologies Myopac equipment used with participants). Wrist deviation was measured using the electrogoniometer (also see Fig. 5 for an image of the Biometrics, Inc. sensors used with participants). The subjective level of perceived exertion was measured using a Borg Rating of Perceived Exertion with discrete levels ranging from 0 to 10 (Borg, 1998).

Table 1
Experiment conditions.

	Straight handle	Angled handle
Left foot on floorboard (inside)	IS (5 lifts)	IA (5 lifts)
Both feet on ground (outside)	OS (5 lifts)	OA (5 lifts)

It was hypothesized that the angled handle would require less wrist deviation than the traditional straight handle. Additionally, based on Strasser et al.'s (1996) research, lifting the ICS from the car using the angled handle was expected to require lower muscle activation levels than performing the same lift with the straight handle. Lastly, it was hypothesized that placing a foot in the car would allow the participant to move herself closer to the load, thereby reducing the angle at the elbow (increasing mechanical advantage) and reducing the muscle effort required to achieve the required force in the lift.

2.5. Procedure

Participants were informed that the study was to compare the different ICS handles and their effects on upper body effort in lifting the seat. They were measured for height using an anthropometer, introduced to the experiment equipment, and led in a regimen of stretches of the upper-arm, forearm and lower back. Subsequently, one set of skin surface electrodes was attached to their upper-arm (biceps region) and another set to the forearm (flexor region) of the right arm according to Perotto (1994); see Fig. 6. The flexor carpi ulnaris was located by stretching a rubber band, marked in thirds, between the posterior portion of the medial epicondyle and the posterior portion of the styloid process of the ulna. Electrodes were placed on either side of the proximal third waypoint. Specific electrode placement, using the rubber band, was used in attempt to minimize cross talk between forearm muscles. However, it should be assumed that EMG results from this placement are a composite of multiple flexor muscles with a strong contribution of the flexor carpi ulnaris. Biceps electrode location was determined by identifying the greatest bulge during arm flexion while holding a 2.3 kg weight (Perotto, 1994).

In order to establish a resting baseline response, participants were asked to rest for 3 min and then EMG data were recorded for 60 s while the participant continued to rest. They were then asked to hold a 2.3 kg weight (dumbell) in a 90° biceps curl with the elbow beside the hip and to flex their wrist. EMG data were recorded for this reference task while the participant maintained the defined posture position for 10 s.

An experimenter demonstrated the ICS lift from the back seat of the car with the left foot on the floorboard and with both feet outside the car. Participants were then allowed to practice both lifts until they felt comfortable with each one (verbal response). The
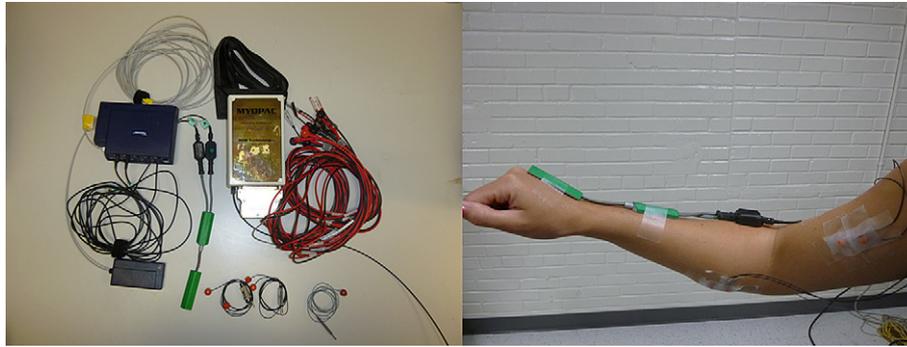
Fig. 5. Electrogoniometer and EMG equipment.

electrogoniometer was subsequently attached to a participant's right wrist and calibrated for their maximum range of motion. The participant then began testing with blocks of condition trials presented in random order. Each condition block included five lifts (see Table 1) and participants were asked to complete the Borg scale at the close of each block. The ICS handle was changed between blocks, if necessary. Once participants completed the 20 lifts, the skin surface electrodes and the electrogoniometer were removed from the participant's arm, and they were excused.

For each participant, ulnar deviation (UD) data were collected with a sampling frequency of 2048 Hz and normalized based on the maximum range of wrist motion calibrated for that participant using the following formula:

$$\text{Normalized UD} = \frac{\text{Raw UD}}{\text{Calibrated Max UD}}$$

The maximum UD after normalization for each test trial was used in the subsequent statistical analysis.

Biceps and flexor EMG data were collected with a sampling frequency of 1024 Hz. The original data were rectified by taking the absolute value of the entire signal and applying a fourth-order Butterworth high-pass digital filter with a 20 Hz cut-off to remove movement artifacts. A fourth-order Butterworth low-pass filter, with a cut-off frequency of 500 Hz, was also applied as an anti-aliasing filter. Finally, a Butterworth notch filter was applied to remove the power line noise occurring within the 59–61 Hz range. All EMG signals were manually plotted and inspected for any additional spikes and outliers, after applying the filtering techniques. EMG amplitude was normalized using the response for the known level of force condition (Rash and Quesada, 2002) of 2.3 kg. The normalized value, or relative activity, was calculated using the following equation:

$$\text{Normalized EMG} = \frac{\text{EMG}_{\text{Task}} - \text{EMG}_{\text{Rest}}}{\text{EMG}_{\text{5lbs}} - \text{EMG}_{\text{Rest}}}$$

The maximum muscle response signal after normalization for each trial was used in the subsequent ANOVA model.

3. Results

3.1. Data analysis

Descriptive statistics for all responses variables across participants are presented in Tables 2 and 3 (also see Figs. 7–9). The EMG and UD responses are presented in normalized units. Borg scale results are in original subjective ratings.

Table 2 suggests that handle design may have some effect on flexor activation, with the angled handle requiring less flexor activation as compared to the straight handle design. Separately, the angled handle required more biceps activation as compared to the straight handle. The perceived exertion was slightly less for the angled handle, according to the Borg result. There was no evidence of a change in UD. Table 3 shows less flexor activation as a result of placing the foot inside the car during the lift. The table also shows more biceps activation when the foot was placed inside the car. Differences in UD and Borg ratings were minimal.

All response data were inspected for potential outliers using box plots. Results revealed the EMG and Borg data to be absent of outliers; however, there were several UD data points with statistically large deviations from the mean response. Review of test videos showed equipment or sensor attachment problems for two trials, which were removed from the analysis.

3.2. Ulnar deviation

An ANOVA was applied to a statistical model of the UD response in handle type, foot placement and the interaction of effects. Results showed that significantly less UD occurred when the participants placed their left foot-in-car versus both feet on the ground $(F(1,185) = 4.22, p = 0.04)$. However, no main effect of
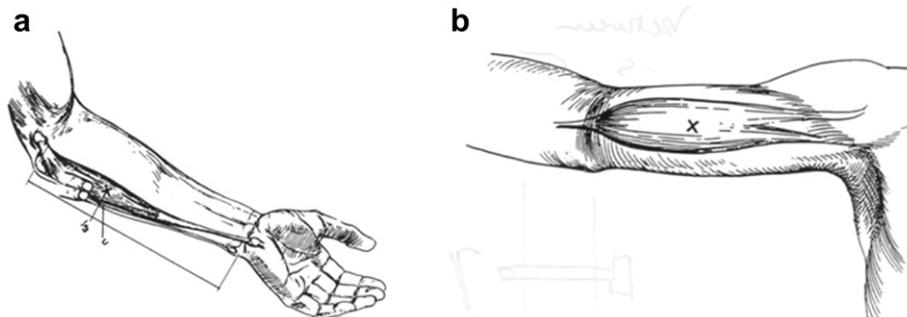

Fig. 6. EMG electrode placement locations.

Table 2
Descriptive statistics of all response variables grouped by handle design.

Handle	N	Variable	Mean	SD
Angled	100	Flexor	2.625	1.297
	100	Biceps	2.485	0.745
	99	UD	0.426	0.080
	20	Borg	3.775	2.155
Straight	100	Flexor	2.949	1.564
	100	Biceps	2.334	0.632
	99	UD	0.426	0.084
	20	Borg	4.175	2.267

handle design was found ($F(1,185) = 0.30$, $p = 0.584$). Based on observations during the experiment, participants compensated for wrist deviations from a neutral posture when using the straight handle by relaxing their grip and maintaining a relatively consistent wrist angle. No interaction effect of handle with foot placement was found ($F(1,185) = 1.29$, $p = 0.258$).

3.3. Flexor EMG

An ANOVA model was constructed to test the main effects of handle design and foot position on flexor EMG activation. Diagnostics on model residuals revealed violations of the constant variance assumptions of the ANOVA test. Consequently, a logarithmic transformation was applied to the normalized EMG data, and the ANOVA was replicated using the transformed data with success. Results revealed the angled handle to produce significantly lower flexor EMG activation than the straight handle ($F(1,187) = 13.35$, $p = 0.0003$; see Fig. 7), which was consistent with the hypothesis. However, there was no significant main effect of "foot position" factor ($F(1,187) = 1.21$, $p = 0.273$) or an interaction effect between handle design and foot position ($F(1,187) = 0.0014$, $p = 0.9705$)

3.4. Biceps EMG

An ANOVA model was also applied to test the main effects of handle design and foot position on biceps EMG activation along with the interaction of terms. Diagnostics on model residuals revealed expanding variance of observations for higher predicted values of the response even after transformation (log). Consequently, an additional square root transformation was applied to the normalized EMG results, and the ANOVA was replicated using the transformed data with success. Consistent with hypothesis, main effects of handle ($F(1,187) = 4.02$, $p = 0.046$) and foot position ($F(1,187) = 4.53$, $p = 0.035$) were found (see Figs. 7 and 8). Specifically, the angled handle resulted in higher biceps activation than the straight handle. This indicated that the redesigned handle led to greater upper-arm muscle use instead of use of the smaller flexor forearm muscle. Additionally, results showed lower biceps

Table 3
Descriptive statistics of all response variables grouped by foot position.

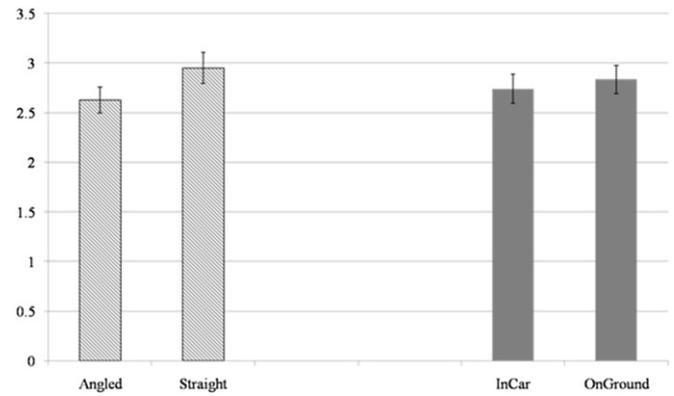| Foot position	N	Variable	Mean	SD
In car	100	Flexor	2.739	1.461
	100	Biceps	2.469	0.684
	99	UD	0.423	0.083
	20	Borg	3.900	2.309
On ground	100	Flexor	2.835	1.429
	100	Biceps	2.351	0.700
	99	UD	0.429	0.081
	20	Borg	4.05	2.127

Fig. 7. Plot of flexor EMG activation across test conditions.

activation when participants stood with both feet on the ground than when they put their left foot in the car. This might due to the participant's arm posture, which was closer to a 90-° angle at the elbow when lifting with their foot inside the car. No handle by foot placement interaction was found ($F(1,187) = 0.03$, $p = 0.873$).

3.5. Perceived exertion with the BORG scale

A nonparametric version of the ANOVA model was used to analyze the Borg data due to individual differences in internal scales of physical exertion (i.e., certain subjects consistently provided ratings in a higher range). Rankings were assigned to each participant's ratings and used as the DV in the ANOVA model. Results revealed a marginally significant main effect of handle design ($F(1,27) = 3.462$, $p = 0.07$). The participants rated the perceived exertion lower when lifting the ICS with the angled handle than with the straight handle. However, no significant differences were found for foot position ($F(1,27) = 0.015$, $p = 0.90$) and no significant interaction with handle type was found ($F(1,27) = 0.754$, $p = 0.393$). Given that a significant main effect of foot position was observed for the biceps EMG response, the subjective Borg scale rankings might be less sensitive than the physiological measure for evaluating the level of muscle exertion.

3.6. Correlation analyses

The physiological responses were averaged across the five trials per condition per subject. These means were pooled with the Borg scale data for correlation analysis. A series of partial correlations were determined among the four response variables (see Table 4).
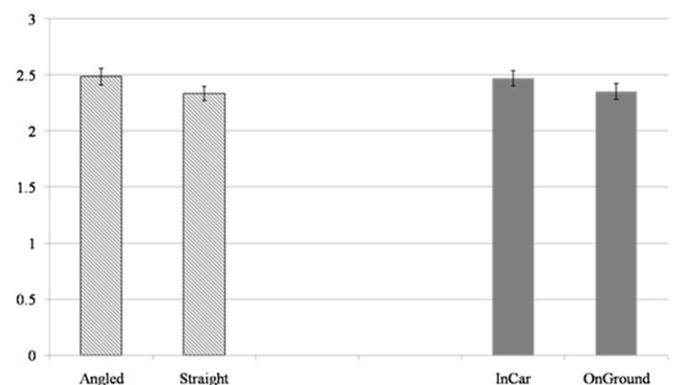

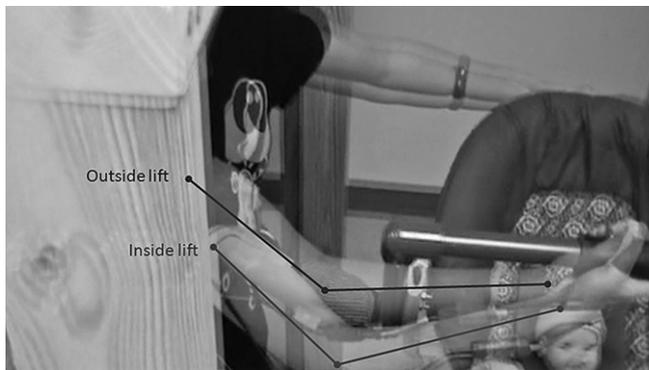**Fig. 8.** Plot of the biceps EMG activation across test conditions.

Fig. 9. Outside and inside lift arm positions.

This type of analysis investigates the relationship between two response variables (e.g., flexor EMG and Borg scale) by removing the effects one or more other variables on the relationship of interest. Results revealed a significant negative correlation between flexor EMG and UD ($\rho_{\text{flexor EMG,UD|bicep EMG, BORG}} = -0.425$, $p = 0.008$), and a marginally significant positive correlation between flexor EMG and biceps EMG independent of condition ($\rho_{\text{flexor EMG,bicep EMG|UD, BORG}} = 0.292$, $p = 0.075$). These results indicate that (1) participants applied a smaller flexor force when ulnar deviation was greater, and (2) the flexor and biceps muscles tended to co-activate during the lift. No significant correlations were found between the subjective ratings of perceived exertion and physiological responses (see Table 4).

4. Discussion

The results of this study revealed significant differences between the angled handle and the traditional straight handle design with support for the new design in terms of reduced forearm muscle activation and perceived exertion. Differences were revealed through parametric analysis of the transformed data set, which were supported by plots in the original units (see Table 2 and Figs. 7 and 8). The straight handle was actually superior in terms of reducing upper-arm muscle activation. Results also revealed user foot placement in lifting the ICS to differ in postural and muscles response with the in-car position advocated in the popular press reducing wrist deviation but leading to increased upper-arm muscle activation. (This was possibly due to an increase in mechanical advantage, which we address below.) The correlation analysis confirmed that UD mediates flexor force, as expected.

It was expected that muscle activation in the biceps would decrease when lifting the ICS with the angled handle; however results were opposite to this. Our findings suggest that the angled handle provided a means for users to transfer effort from the smaller flexor muscle group to the larger biceps muscle group, thereby increasing the efficiency of the lift and reducing overall exertion. The Borg ratings also support this inference. This may be consistent with previous studies that identify muscle strength as

a factor when selecting a lifting strategy (Li and Zhang, 2009), however follow-on work would be required to verify this claim for ICS lift postures. Another reason for the increased biceps activation could be the biceps' role in forearm rotation. As the ICS was removed from the base, the load rotated about the handle due to its new center of gravity. When lifting with the angled handle, this rotation caused forearm pronation, which the participant resisted by flexing the biceps. Therefore the angled handle and neutral wrist posture could introduce additional biceps activation in stabilizing the load. This pronation would not necessarily occur with the straight handle, as the ICS could sway freely due to the grip posture (addressed below) and skin movement on the surface of the palm.

No significant difference in ulnar wrist deviation between the straight and angled handles was observed. This result can be explained based on the findings of the cited MMH studies. Drury et al. (1985) described how operators altered their grip posture and reduced grip force in order to minimize wrist deviation. The Borg scale demonstrated that participants' perceived exertion was less when using the angled handle compared to using the straight handle, which is also consistent with this explanation. That is, the straight handle caused UD and discomfort, which was reflected in the ratings.

Although the effect of foot position on UD was statistically significant, the difference in the normalized scores was only 0.006, which is not likely to cause any practical differences in the lift. However, biceps activation proved to be lower for the out-of-car foot position. A visual comparison of the lifting arm posture for the two foot position conditions is shown in Fig. 9 with superimposed photos of one subject using the straight handle ICS across multiple trials.

Lines are used to reveal the general upper and lower arm positions for the in-car foot placement on the bottom and the out-of-car condition on top. The figure shows how placing the foot inside the car allowed participants to move their upper body closer to the load and bend the elbow closer to a 90-° angle. In terms of mechanical advantage, a 90-° angle at the elbow is an optimal lifting posture for the biceps. Moving closer to the load might have allowed participants to generate greater force through the biceps rather than relying on the flexor group. Consequently, we observed a greater degree of biceps effort for the in-car condition.

No significant results were found from the flexor activation or Borg scale data due to foot position. This lack of significance could be attributed to many different factors such as varying lifting styles among participants. For example, some participants bent their torsos and leaned inside the car for the out-of-car foot placement condition. Others participants simply reached their arms into the car and lifted out the ICS. Table 5 provides a summary of the significant results for each response. The handle orientation and lift strategy that resulted in less muscle activation/UD is noted for each DV, and no condition is included when the response was not significant.

The results of evaluating the lift recommended by Consumer Reports were mixed. Although the increased biceps activation suggests an in-car foot placement is more efficient than out-of-car, experimenter observation of door frame strikes during the ICS lift revealed the seat was more likely to be bumped during the foot-in-car condition (84) versus out-of-car (48). This could create new

Table 4

Partial correlation between two response variables, given the effect of other controlled variables.

	Borg	Flexor	Biceps	UD
Borg		0.174 (0.295)	−0.113 (0.499)	0.207 (0.212)
Flexor			0.292 (0.075*)	−0.425 (0.008**)
Biceps				−0.063 (0.706)
UD				

Table 5

Summary of results: optimal condition for each response.

	Flexor	Biceps	UD	Perceived exertion
Handle	Angled	Straight	–	Angled
Foot position	–	Outside	Inside	–

complications for the lifter and undesired reactions from infants. When using the foot-in-car method, the user has the advantage of better supporting their center of gravity while performing the lift; however, there is the added challenge of balancing the body and the elevated ICS while removing their foot, body and ICS from the car. It is possible that bumping into the car door opening may compromise the safety of the infant, which would be of greater concern for a parent. Through consideration of these findings, even though the lift recommended by Consumer Reports is less taxing in terms of muscle activation, the other factors outweigh that benefit and make it a more difficult lift.

4.1. Comparison with other studies

The electrogoniometer results show that lifting with a foot in the car requires less UD than lifting from the outside. The MMH and hand tool design literature demonstrates that wrist deviations can result in a weaker grip that could compromise the load (Drury et al., 1985; Lewis and Narayan, 1993; Moore et al., 1991; Strasser et al., 1996). Since increasing the UD may reduce the grip force during a lift and increase the potential for loss of control, our findings generally support the recommendation found in the popular press of putting one foot in the car to lift the ICS.

5. Conclusion

The results of this study may be used to improve future ICS handle designs or as a basis for informing those purchasing or using an ICS. Such a design effort would be worthwhile, since removing an ICS is a difficult lift, especially for smaller individuals, which is part of a necessary task. In fact, when compared to lifting tasks performed by professionals in industry (Dempsey, 2003), manually hoisting an 11 kg car seat out of the vehicle modeled in this study was analogous to lifting a 60th percentile weight at a 90th percentile horizontal distance from the body. Furthermore, industrial lifts are meant to be performed with two hands. Lifting a car seat may be even more challenging than some industrial lifting tasks since it is an asymmetric lift with one hand directly over the center of gravity of the load with the other hand balancing from one side. Not only is this lift taxing for any worker by industry standards, it is extremely taxing for small members of the population, such as the 20th percentile stature women tested in this study.

5.1. Limitations and future study

This study was conducted using a car mock-up based on a Honda Accord, limiting application of the results to other vehicle types, such as sport utility vehicles (SUV) and minivans, which have different seat heights and different sized door openings. The study should be replicated for other vehicles to validate results. Likewise, expanding the participants' stature beyond the 20th percentile female used in this study would be of additional benefit. Different doorway and user anthropometric combinations may produce different lifting strategies and patterns of influence of ICS handle designs on user posture and muscle responses. Such research would help inform designers and consumers about varying ideal ICS design based on user behaviors.

User adjustments to posture at the elbow and upper-arm were observed during the experiment but not formally recorded. It is possible that such kinematic data may serve to further explain the wrist posture data and EMG responses recorded in the present work. Another aspect of the ICS lift that was not formally recorded

was user grip force at the ICS handle. Such force measurements could be related to the wrist angle as described in the literature. It would then be possible to determine whether users trade grip force and load stability for postural comfort under UDs imposed by straight ICS handles in seat lifting.

The study was also limited in terms of the number of muscle groups that were observed during the test trials. Activation of other muscles related to the lift, such as those in the shoulder and back, was not observed, but may still have been an important component of the lift affected by handle design and foot placement. In addition to reducing flexor effort and increasing biceps effort when lifting with the angled handle, participant may have transferred some of the weight of the ICS to different or larger muscles that were not considered.

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