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# Variability and misclassification of worker estimated hand force

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**Title:** Variability and misclassification of worker estimated hand force

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### **Abstract**

Ergonomic studies often use worker estimated hand force reproduced on a dynamometer to quantify force exposures but this method has not been well-studied in real work settings. This study evaluated the validity of worker estimates of hand force in a field study and determined the misclassification of worker estimated hand force exposures compared to directly measured forces. Eight experienced sheet metal assemblers completed ¼-inch diameter fastener installations using 6 different pneumatic tools. Grip forces were recorded by a pressure mat and were compared to worker estimated forces demonstrated on a dynamometer. Directly measured and worker estimated readings showed moderate correlations (0.53-0.67) for four installation tools and fair to moderate for two tools. The coefficient for variation of force estimates was 65% within repeated subject trials and 78% between averaged subject trials but 69% between subject trials during actual tool installations. Misclassification of worker estimated exposures varied by two cut-points: 29% using 4.0 kg and 49% using 6.0 kg. The force match procedure may provide adequate differentiation of high and low exposures in some settings, but is likely to result in substantial misclassification in other settings.

### **Keywords**

Force Measurement; Hand Force; Exposure Rating

### **Introduction**

Ergonomic studies depend upon quantified physical exposures of work activities to guide prevention efforts in the management of work-related musculoskeletal disorders. Many exposures are difficult to collect in the work environment, and gathering information on hand force exposures present some unique challenges. Force has been most consistently linked to the development of many work-related musculoskeletal disorders (Panel on Musculoskeletal Disorders and the Workplace, 2001) so it is important to explore appropriate methods for quantifying force exposures in various work settings. The challenge of quantifying measures of hand force is caused by its complex nature. Force is transferred through direct physical contact with tools and other objects in multiple directions. A variety of factors including grip forces of the palm and fingers and feed forces that push through the arm and palm combine to produce force on a tool or object (Welcome et al., 2004). Force is also affected by tool characteristics including handle design, mass, center of gravity, and the typical duration of the operation, making it important to measure force during performance of actual tasks (Lin et al., 2003). There are several types of data collection methods used to quantify exposures including direct measurement, observation and subjective methods. There is a trade-off in validity as well as cost and practicability of use between these methods. Collecting force data using direct measurement involves placing sensors in or on the work equipment or attaching them to the worker's body to record the physical effort produced by the muscles of the body (Bao and Silverstein, 2005; DiDomenico and Nussbaum, 2008). Generally, data collection using direct measurement occurs in the laboratory since

the instrumentation is cumbersome and often invasive to the work environment; but laboratory settings may lose some of the workplace environmental factors that influence exposure levels such as the stability and orientation of the work materials, speed of production, and tool performance. Direct measurement is considered the most precise and accurate, but is costly to collect. Observation methods that are commonly used to record repetitive motions and awkward postures are less useful for capturing the true measure of muscular effort.

Observer-ratings on an ordinal scale can discriminate between jobs requiring higher and lower hand forces but the force rating may not represent the actual force level. Subjective methods offer a simple way to collect force estimates such as worker self-reported ratings on a Borg scale or worker demonstrated force estimations on a hand-held dynamometer (Borg,1990, Bao 2005), but generally produce less accurate estimates of force level than direct instrumentation (Buchholz et al., 2008). Validity of the results from subjective methods depend on a worker's ability to accurately estimate the physical exertion used during task performance.

Hand grip "force matching" is one subjective method commonly used by ergonomists in field studies. In this method, the worker estimates the physical hand grip requirements of a task by simulating the force required on an instrument such as a hand force gauge or dynamometer (Bao et. al, 2006; Casey et al., 2002; King and Finet, 2004). The worker typically performs the force estimation immediately following performance of the actual task to produce the best recall (Lowe, 1995). Controversy exists as to how accurately individuals perceive their own level of exertion and their ability to replicate the force required, particularly when other factors such as object size and shape, motion, vibration, and posture come into play (Buchholz et al., 2008; King and Finet, 2004).

Most studies evaluating the usability of the hand grip force match procedure have been conducted in a controlled laboratory environment (Bao and Silverstein, 2005; Koppelaar and Wells, 2005; Marshall et al., 2004). These studies have explored volunteers' ability to replicate specific hand force levels (King and Finet, 2004; Kumar et al., 1997; Lowe, 1995), the accuracy of simulating force from simple tasks that were familiar to volunteers, and the effect of training in the force match procedure to improve the precision of estimates. Results have varied regarding the accuracy and precision of force matching when compared to known forces in instrumented handles or tools (Koppelaar and Wells, 2005). Few studies have examined forces generated by tools used in specific work environments (McGorry et al., 2004). Despite limited testing of the force match procedures in field studies, the methods are commonly used to collect hand force information for prevention and intervention studies. It is important to examine the usability of methods in actual work environments even if the methods show promise in laboratory testing. In this study, we evaluated the validity of worker estimates of hand force among experienced sheet metal assemblers using fastener installation tools, and determined the degree of exposure misclassification that could be caused by using worker estimates instead of directly measured force values.

## **2. Methods**

Eight employees from a local company, experienced with the use of fastener installation tools, volunteered for the study and provided informed consent approved by the Institutional Review Boards of both our university and the company sponsor. The data used in the current study was collected as part of a larger project whose purpose was to design a protocol for measuring workers' physical

exposures from tools used by sheet metal assemblers at this company. The methods pertinent to the current study are described below.

## **2.1 Materials**

Hand force was directly measured by pressure mapping sensors applied to the hand in a 7 cm x 7 cm flexible mat developed by Novel gmbh<sup>TM</sup> (Munich, Germany). The small mat contained an array of 16 X 16 miniature variable capacitance load cells. The pressure range of each load cell was 5-200 kPa with a sensing element area of 4.4 X 4.4 mm and mat thickness of <1.2 mm without the coating. The mat recorded pressures applied perpendicular to the sensor while minimizing the effects of shear forces. The design of the mat allowed each load cell (sensor) to move within the flexible mat to position the sensor perpendicular to the skin and tool surfaces, to enable maximal pressure recordings. Pressures were recorded at a rate of 70 samples per second, recorded in newtons per centimeter-squared. The sensor area was determined by the number of cells active at each sampling time. These data were recorded to the Novel Pliance<sup>TM</sup> electronic analyzer software program on a conventional computer. A previous study showed good reliability of hand force measured using the pressure sensors (Lemerle et al., 2008),

Perceived estimates of hand force effort were collected using a dynamometer (North Coast<sup>TM</sup> Hydraulic Hand Dynamometer, California, U.S.A.), a hand-held device that contained a single load cell inserted into a handle with force readings displayed on a dial. The handle of the device was adjustable to various diameters (range: 3.5 to 8.7 cm) and circumferences (range: 10.2 to 20.7cm). The handle had a gently sloped open Ushaped contour that followed the natural curve of the palm. This device has shown reproducible and valid results for test-retest in other studies (Harkonen et al., 1993; Janda et al., 1987).

The test instruments were six different pneumatically powered installation fastening tools that are commonly used in this industry. Each tool installed ¼-inch diameter metal fasteners using a rotational mechanism for threaded fasteners or a pulling mechanism to install pulled blind fasteners. The tools differed in handle design with three tools containing pistol grip handles and three tools with inline handles. The inline tools had smooth, cylindrically shaped straight handles. The tool activation was a thumboperated lever that extended from the side or end of the tool, separate from the tool handle. The pistol-handled tools had oval-shaped straight handles except for tool 3 that had a gentle contour along the handle length. The pistol-handled tool activation was a trigger mechanism located independent from the handle, which was operated by the index finger. The activation mechanisms were not covered by the pressure mat. Several tool and fastener characteristics are listed in Table 1.

## **2.2 Procedures**

The current study used active experienced workers who were unfamiliar with the force matching technique. The method for testing was similar to field studies with workers performing an actual work process immediately followed by performing the same hand activity on a dynamometer. For these force matched estimation trials, workers were told to simulate installing a fastener while holding the dynamometer. Subjects were given an opportunity to practice force matching on the dynamometer prior to the start of the study as is commonly done to collect data in the field and these trials were not recorded. The Novel<sup>TM</sup> flexible mat was attached to the palm of the subject's hand with a self-adherent wrapped tape. To minimize residual loads produced by postural changes during testing, the hand and arm were placed in the test position and the system was reset to zero prior to each trial. The subject

held the same hand posture during the directly measured fastener installation trials shown in Figure 1a and the worker estimated trials on the hand dynamometer shown in Figure 1b, and the technician exchanged the tool with the dynamometer between trials. The dynamometer handle diameter was set as closely as possible to approximate the diameter of the tool used in the installations, and the subject held the dynamometer in the same posture as during the tool trial.

Initially, the strength of the workers was measured to compare to values of a normal population. Each subject completed three trials of maximum grip with the shoulder positioned next to the body and the elbow at 90 degrees of flexion. For the force match procedure, each subject grasped the tool handle using his typical work posture and installed the fasteners as he would during normal work. Each subject completed a series of 10 fastener installations with three force estimation trials following the fourth, fifth, and sixth fasteners. The series of fastener installations and force estimation trials on the dynamometer was repeated for six fastening tools. The tools were presented in a random order. The eight subjects installed 10 metal fasteners with each of the six tools for a total of 60 installations per operator and 480 fasteners installed for the study. The pace of work to install the fasteners was similar to the speed that workers would have used to install fasteners during typical work activities. Video recordings of at least 3 trials of each series were taken. Each data collection session lasted 1-1.5 hours for a single subject.

### **2.3 Statistical Analysis**

To compute force values (N), we summated the pressure readings (N/cm<sup>2</sup>) and divided by the area of the active sensors at each time point. A peak force showed the highest force value at any time point during a single trial. A mean force averaged the force readings across all time points of each trial. We computed the mean of all force-estimated trials and the mean of the matched directly measured trials. We evaluated the validity of the mat pressures by comparing agreement between the mat pressures taken from the dynamometer handle and the readings from the dial of the dynamometer using Pearson's correlation. We compared differences in the area of hand contact of the active mat sensors while holding the tool and while holding the dynamometer for matched trials using a t-test. We reviewed video recordings to note postural changes of worker's hands and wrists during installation trials. Descriptive statistics showed the peak and mean grip force values, the coefficient of variation for each subject and tool, and the estimation error [(difference of the directly measured trial and matched estimation trial)/ directly measured trial]. We measured consistency of force values between the directly measured and estimated trials using the mean values and matched trials with Pearson's correlation coefficient. Since the misclassification of physical exposures may show an inaccurate

association of exposures with health outcomes of workers, we explored the proportion of misclassified cases that would occur from estimated hand forces obtained using the forcematch method. We used two cut-points to categorize high and low force levels, based on cut-points that have been used in other studies for identifying cases with hand/wrist disorders: 4 kg and 6 kg (Silverstein et al., 1986; Sluiter et al., 2001). We determined the proportion of cases that would have been misclassified by force match estimates when compared to direct measurement, and examined whether the misclassified cases underestimated or over-estimated the directly measured force value. All analyses were performed using SPSS 16.0 (2007) analytical software.

### 3. Results

All eight subjects were right-handed males with a mean age of 56 years and an average employment time at the company of 24 years (range 10-45). The subjects' average right hand grip of 468.5 N (95% CI 434.3-502.8) was 4% higher than population grip strength for age and gender (Mathiowetz et al., 1985). The duration of installation time was between two and four seconds per trial for all tools. Time between trials ranged from 21 to 528 seconds (41seconds mean; 32 seconds median). Validity testing showed good results with high correlations of the simultaneous recordings of the mat and dynamometer ( $r = 0.97$ ,  $n=165$ ) as graphically shown in figure 2. A linear regression of the mat sensor readings obtained while holding the dynamometer to the readings off the dynamometer dial accounted for 93% of the variance with a beta estimate of 0.77 and an intercept of -15.95.

The estimated force readings on the dynamometer shown in table 2 had a wide range of values and the directly measured peak and mean force readings are lower than the estimate force values. Comparison of the mean of directly measured peak force readings to the mean of the force estimated readings showed good correlation values for four tools with lower correlations for the other two tools as shown in table 2. Results were similar for the comparisons of the directly measured mean values to estimated force values (correlations ranged from 0.04 to 0.68) but the estimation errors were larger for the mean force trials (range of values 18% to 207%).

The coefficient of variation (CV) that describes the variability within repeated trials showed high variability within the force estimation trials across all subjects (CV mean = 65%) and across all tools (CV mean = 78%). There were similar inconsistencies found during the directly measured tool trials despite using experienced workers (CV mean = 69%).

Figure 3 shows the range of force values for the directly measured peak values and the dynamometer force estimations of each tool. The results of the estimation of error  $[(\text{actual}-\text{estimate})/\text{actual}]$  used as a measure of validity was quite varied between tools with an error range of 2% to 176%. Examination of estimation errors by subjects across all tools showed four individuals had error rates of less than 20% but the other subjects' error rates were remarkably higher (91%, 170%, 205%, 253%). Subjects with high estimation errors occurred with at least two of three specific tools (Tools 4, 5 and 6). A comparison of the number of active sensors of the pressure mat that were in contact with the hand and tool during the directly measured trials to the active area from the dynamometer force estimations for each tool showed no significant difference in total area except with tool 5 ( $p=0.01$ ), indicating similar hand posture between the tool grip and the grip on the dynamometer for five of six tools. There were few occurrences of sensors reaching the maximum pressure (0.00027%). Video recordings of 210 (44%) of the installation trials showed no meaningful postural changes for four tools (Tool 2, 3, 5, 6). Tool 1 showed modest postural changes of the wrist for most trials (93%) and tool 4 showed minimal wrist movement but these postural changes occurred at the end of the installations when the fastener was seated.

We evaluated the number of trials that classified the estimated force similar to the directly measured force. Each estimated and directly measured force was assigned a value as above or below a cut-point. The selected cut-points have been used to identify high and low hand force levels in studies investigating an association between hand force and hand and wrist disorders in workers. Using a 2X2 table, we showed that the proportion of cases with the same classification (high or low force) was 71%

with the 4.0 kg cut-point and 51% with the 6.0 kg cut-point. We examined the occurrence of misclassification of trials for the 4.0 kg cut-point and found 4% of the trials under-estimated the force level on the dynamometer compared to the directly measured values and 25% over-estimated the force. For the 6.0 kg cut-point, 41% under-estimated the force level and 8% over-estimated the force level of the misclassified cases.

#### **4. Discussion**

This study evaluated the validity of force matching in a field study using hand force estimation procedures commonly used by ergonomists (Bao et al., 2006). The subjects selected for this study were unfamiliar with the force match procedure and received only a brief introduction and opportunity for practice prior to data collection which is the typical scenario in many field studies. The results showed that subjects had inconsistent responses and large coefficients of variation among repeated estimation trials as well as among multiple trials of direct measurement of the actual fastener installation. The force estimation method produced reasonably valid results for three of the six tools as evidenced by the low level of estimation errors and modest correlations. The three tools with high estimation errors may be due to a poor interface of the tool and pressure mat (tool 5) or caused by the nature of the tool operation (tools 4 and 6). Tool 5 showed significant differences in area of coverage of the mat on the handles of the tools and the dynamometer and this affected the pressure readings. Tool 4 was a light weight tool that required a low hand force to operate the tool during the installation; tool 6 was a heavier tool (4.3 kg) and used a pull force with a “break” at the end of the operation that may have been difficult to replicate. These two issues were unique to these two tools so it is unknown if this would be repeated with different tools that have the same characteristics.

In order to relate physical exposures to adverse health outcomes, it is important to have valid exposure estimates. Many studies have reported large within subject and/or between subject variability of physical exposures (Burdorf, 1993; Kromhout et al., 1993). The variability may be due to the nature of the work tasks, the environment, or the method for measuring the physical exposures. Force matching gives a subjective estimation of the perceived effort and even though the estimate does not represent the actual force, the values may be adequate for use in epidemiological studies to show a relationship to poor health outcomes. Using cut-points to categorize the force estimates as high or low exposure can result in misclassification of cases so researchers should be cautious in applying defined cut-points to estimated values.

The current study was intended to mimic the way data collection occurs in ergonomic field studies since most companies cannot afford to have workers taken off the assembly line for extended periods of time. The worker volunteers were given specific instructions about the force match procedures and they had the opportunity to practice the protocol before the start of data collection. The procedure for testing initially had each subject install four fasteners with a single tool to help them adjust to the test set-up before performing the first force match trial. Despite these efforts, there was large within subject variability, and this occurred within the estimation and the directly measured trials. Factors contributing to this variability may have included the short time (2-4 seconds) required for installation of each fastener, the low force required to hold and operate the tool during the installation, and subtle differences between arm and fastener position in successive trials. Some researchers have found a tendency for more frequent misclassification and exposure underestimation in tasks with low force levels (Kumar et al., 1997; Lowe, 1995; McGorry et al., 2004) and this may account for the large

estimation errors found in tool 4 of the current study. McGorry and colleagues (2004) reported a high mean error of estimation (194.7%) in more complex tasks such as meat cutting even when performed by experienced meat cutters. The high variability of grip force measured among individual experienced workers while performing the same task with the same tool demonstrates the inherent variability of hand force exposures in workplace settings, a fact that poses a significant challenge for all methods of exposure assessment.

We found high estimation errors within some tools and these variable responses occurred more frequently in four of the eight subjects. This indicates that some subjects were less able to perceive and reproduce efforts, particularly for some tools. This is not surprising as there is a wide range in human abilities (memory, physical strength, cognition) so it is likely that some subjects are more aware of physical performance and therefore able to replicate forces during estimation (Casey et al., 2002). The large errors among some subjects may indicate the lack of understanding of the force match process. Training was not a part of this protocol; some studies that have emphasized training and used a reference for force estimation report improved precision of estimates (Marshall et al., 2004; Spielholz, 2006) but others found no difference (McGorry et al., 2004). Ideally, several workers would provide estimated values on several trials of a particular task to reduce the effects introduced by worker variability.

This study had several limitations. Using the pressure mat may have altered the normal tool-hand interface and the tactile feedback from the fastening operation and therefore contributed to some of the variability in the measurement. In addition, the mat sensor was designed to detect perpendicular forces, so shear forces that may have been present with some operations would have been missed. Most tools used a rotational mechanism to install the ¼-inch diameter threaded fasteners; the small fastener size, light weight tools, and relatively low hand forces would have produced minimal shear forces during the installations. A comparison of the mat on the dynamometer to the dynamometer readings showed a 23% lower force value indicative of some loss in detected pressures, although the area of coverage of the mat on the tool handles were similar to the dynamometer handle mat area for most tools. Lower measured pressures from nonperpendicular forces may lead to lower correlations and larger estimation errors. These problems likely contributed to the lack of agreement shown in some of the tools. In addition, the limited number of workers tested may have contributed to some of the variability in results. The installation tools used in this fastening operation required a generally low hand force and a short duty cycle, both of which may have affected workers' ability to reproduce estimated forces.

The strengths of the study are the measurements taken from experienced workers, using the tools, materials, and work procedures that exist in an actual work setting. We tested the validity of force matching, a method commonly used by researchers and consultants to obtain hand force estimates from work tasks in manufacturing settings.

Our results suggest that force matching provides a reasonable estimate of hand grip forces for some tools under field research settings. Further investigation is needed to determine the validity of using the force match method to collect force estimates on tools requiring low forces to operate or with impulsive mechanisms. Use of direct measurement techniques will provide more accurate estimates of exposures, but in many settings may result in fewer workers or work tasks being evaluated. Common to epidemiological study designs is the trade-off between obtaining high quality exposure data on few



subjects versus lower quality data on many subjects. Force matching gives acceptably accurate estimates for some tools and tasks, and will allow more workers or work tasks to be studied.

### **Disclosure Statement**

No authors in this study have actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations within three (3) years of beginning the work submitted that could inappropriately influence this work.

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### Figure Legends

**Figure 1.** Testing set-up for directly measured trial with installation tool (a) and force matched trial with dynamometer (b).

**Figure 1a**

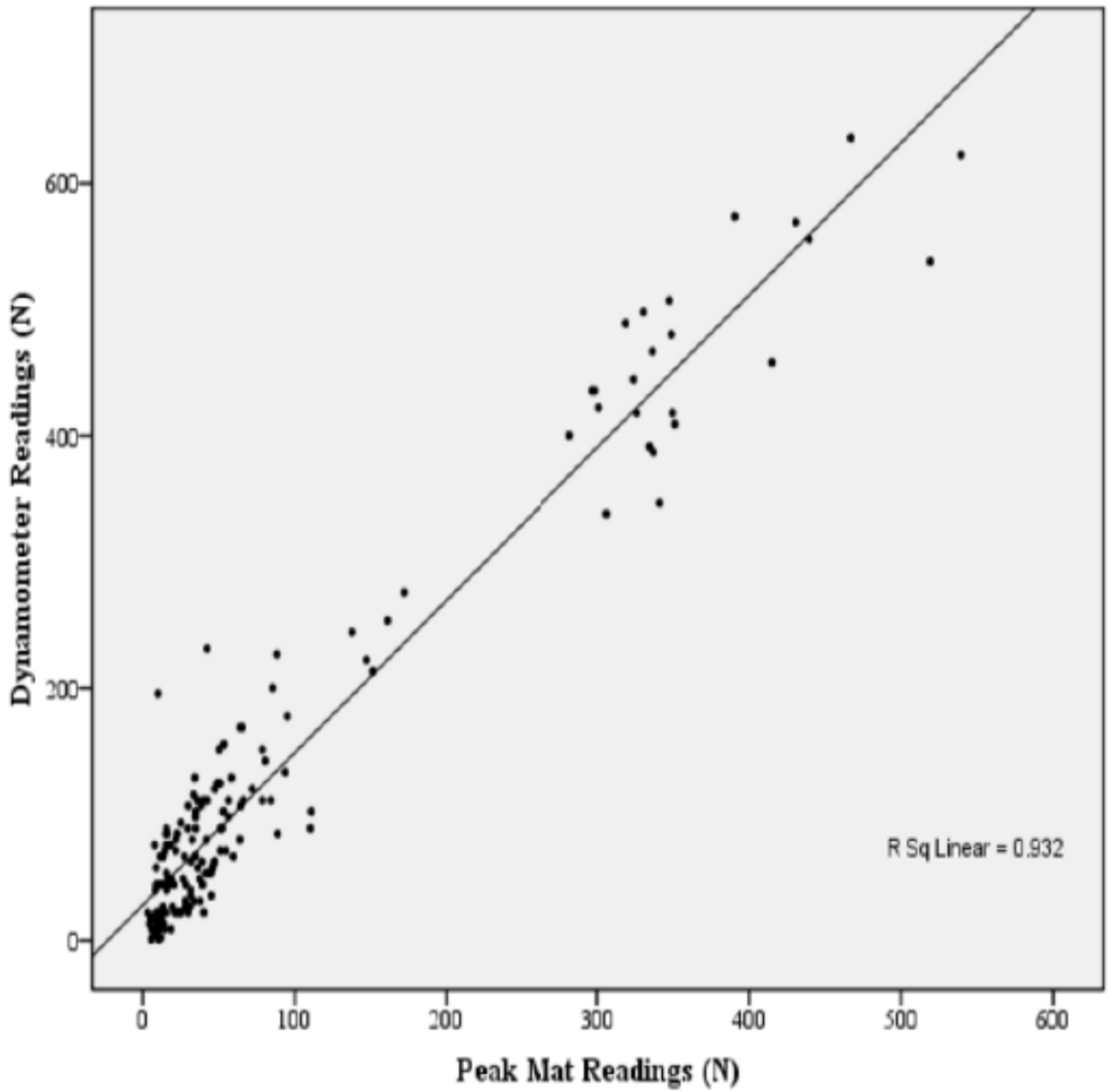


Figure 1b



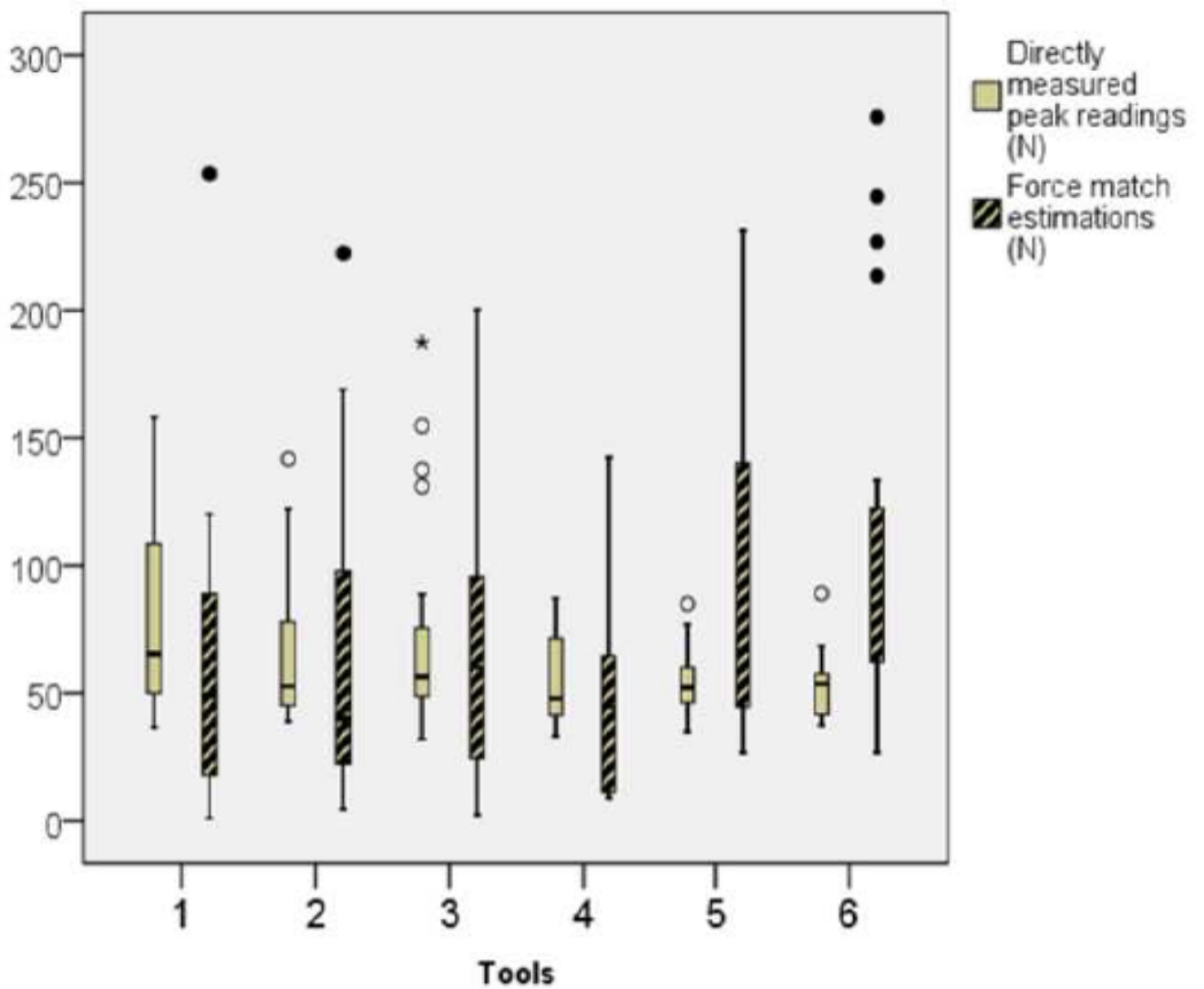
**Figure 2.** Simultaneous force readings from the dynamometer and the pressure mat that was applied to the dynamometer handle during maximum grip testing and force estimation trials.

**Figure 2**



**Figure 3.** Graphical distribution by boxplots of the directly measured peak force readings (dotted) and force estimated readings on the dynamometer (white). The median is the horizontal line in the box. The length of the box is the interquartile range (IQR). Outliers that are between 1.5 and 3 IQR's are labeled as circles (o) and more than 3 IQR's are labeled by an asterisk (\*).

**Figure 3**



**Table 1. Tool and Fastener Characteristics**

Table 1. Tool and Fastener Characteristics

Tool	Tool Type	Tool handle shape	Tool weight (kg)	Tool Handle diameter (cm)	Dynamometer handle diameter (cm)	Maximum Tool torque output (m-kg)	Fastener shank	Type of fastener	Fastener break-off torque (m-kg)
1	Nut Runner	Pistol with offset	1.6	3.7	4.7	3.5	threaded	Steel nut	0.7 – 1.0
2	Jo-Bolt Runner	Inline	1.6	4.1	4.7	4.0	threaded	Blind bolt	0.6 - 0.7
3	Jo-Bolt Runner	Pistol	1.4	4.1	4.7	4.0	threaded	Blind bolt	0.6 - 0.7
4	Nut Runner	Inline	0.9	3.0	3.5	1.3	threaded	Steel nut	0.7 – 1.0
5	Nut Runner	Inline	1.6	4.1	4.7	1.3	threaded	Frangible collar	0.7 – 1.0
6	Lockbolt Puller	Pistol	4.3	4.6	4.7	n/a	pull	Lock bolt	n/a

**Table 2. Estimated forces and comparison measures to directly measured installation trials (n=144)**

Table 2. Estimated forces and comparison measures to directly measured installation trials (n=144)

Tool	Estimated force, in N	Directly measured peak force, in N	Directly measured mean force, in N	Correlation of peak force to estimation trials <sup>#</sup>	CV of estimated force	Average estimation error <sup>†</sup>	Area of mat on tool	Area of mat on dynamometer	p-value*
	mean (SD)	mean (SD)	mean (SD)	r	%	%(SD)	cm <sup>2</sup>	cm <sup>2</sup>	
1	58.9 (56.1)	41.4 (30.1)	19.1 (11.9)	0.67	95	2 (103)	30.3	29.2	0.40
2	66.9 (56.9)	30.7 (23.9)	22.0 (16.9)	0.64	85	20 (86)	31.7	29.0	0.12
3	67.0 (51.3)	35.5 (33.9)	27.5 (25.5)	0.53	77	41 (130)	30.7	28.4	0.11
4	47.6 (37.9)	21.6 (14.5)	15.2 (10.9)	0.03	80	129 (241)	29.2	30.0	0.66
5	96.0 (64.0)	21.1 (11.1)	14.1 (8.7)	0.54	67	158 (191)	29.2	33.0	0.01
6	106.6 (67.9)	20.6 (9.4)	14.7 (6.9)	0.28	64	176 (251)	25.5	26.8	0.41

SD, standard deviation; r- Pearson's correlation coefficient; CV coefficient of variance

<sup>#</sup>Matched trials from directly measured peak and force estimated dynamometer readings

<sup>†</sup> Estimation error = [(force of actual installation – force of estimate)/ force of actual installation]

\* T-test of area of mat on tool handle and dynamometer handle