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# Development of a Dynamic Biomechanical Model for Load Carriage: Phase IV Part C2

## Assessment of Pressure Measurement Systems on Curved Surfaces for the Dynamic Biomechanical Model of Human Load Carriage

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## Abstract

Soldiers experience pressure as a result of their personal load carriage system acting on the shoulder and back. As such, an experimental measurement tools must be able to accurately and repeatability measure pressures on these curved surfaces.

The purpose of this study was to examine pressure measurement systems on curved surfaces resembling the shoulders and the hips. To accomplish this, a method developed by Hadcock (2002) that resolves normal force vectors into vertical and horizontal components was used to test the validity using two different pressure measurement technologies: the XSENSOR® X36 model by XSENSOR® Technology Corporation and the F-Scan (F-socket series) model by Tekscan Incorporated.

The testing jigs used in this study were a cylindrical shape for the shoulder and an elliptical shape for the hips. Under ideal test conditions, results showed that the XSENSOR® had a 2% accuracy error on the shoulder and 4% accuracy on the hip, which is notably better than the 72% accuracy error on the shoulder model and 53% accuracy error for the hip model found for the F-Scan®. The F-Scan® errors were due primarily to working at the low end of the sensor's range and bending the mylar around a 114 mm diameter cylinder that induces a preload on the sensels.

# Résumé

En raison du système de transport de charge personnel, les soldats subissent des pressions qui s'exercent sur les épaules et le dos. Par conséquent, les outils de mesure expérimentaux doivent pouvoir mesurer avec justesse et de façon répétable les pressions s'exerçant sur ces surfaces incurvées.

L'étude en cause avait pour objet d'examiner les systèmes de mesure des pressions s'exerçant sur des surfaces incurvées ressemblant aux épaules et aux hanches. À cette fin, une méthode élaborée par Hadcock (2002) qui convertit les vecteurs de force normaux en composantes verticales et horizontales a été utilisée pour vérifier la validité à l'aide de deux appareils faisant appel à des technologies de mesure de pression différentes : le modèle XSENSOR® X36 fabriqué par XSENSOR® Technology Corporation et le modèle F-Scan (série à prise femelle) fabriqué par Tekscan Incorporated.

Les gabarits d'essai utilisés dans cette étude étaient une forme cylindrique représentant l'épaule et une forme elliptique représentant les hanches. Dans des conditions d'essai idéales, les résultats indiquaient que le XSENSOR® avait une erreur de justesse de 2 % pour l'épaule et une erreur de justesse de 4 % pour la hanche, ce qui est nettement mieux que l'erreur de justesse de 72 % pour le modèle de l'épaule et l'erreur de justesse de 53 % pour le modèle des hanches, relevées dans le cas du F-Scan®. Les erreurs de justesse du F-Scan® étaient dues principalement aux mesures prises à la limite inférieure de la gamme de mesure du capteur et au mylar courbé autour d'un cylindre de 114 mm de diamètre, ce qui induit une précharge dans les capteurs à cellules.

# Executive Summary

## Introduction

To understand how soldiers experience pressure as a result of their personal load carriage system, pressure measurement tools must be able to accurately and repeatability measure pressures on the curved surfaces of the back and shoulders. However, the accuracy and repeatability of modern pressure-sensing systems used on complex curved geometries, such as the human shoulder and hip are currently unknown. A major problem with measuring forces on curved surface areas is that force vectors cannot be compared unless they are resolved into forces in the vertical and horizontal planes. To better understand the performance of pressure measurement systems on curved surfaces, two modern pressure sensors (F-Scan® and XSENSOR®) were tested on simplified curved geometries, including a circular shoulder model and a human-sized elliptical hip model.

## Methods

A mathematical model, developed by Hadcock (2002) from F-Scan® pressure technology to resolve normal force vectors around a curve into vertical and horizontal forces was validated by comparing measured vertical forces, collected by the XSENSOR® and F-Scan® technologies, to actual loads applied on a simple backpack strap. The testing jigs used in this study were a spherical shape for the shoulder and an elliptical shape for the hips. The hip and waist models were validated using a set mass of 9.8 kg and tested for repeatability using 9.8 kg, 14.4 kg and 19.0 kg loads for both the F-Scan® and XSENSOR® sensor pads. Measured output data by the pressure system was then compared to actual applied loads through the backpack strap to determine the accuracy of each pressure-sensing system using the circular shoulder and elliptical hip models. In addition, the test-retest reliability of both systems was examined on the shoulder model using three loads.

## Results and Discussion

Using the Hadcock (2002) method to resolve force vectors into normal forces, the results showed that the F-Scan® had an average 72% accuracy error on the shoulder model when known applied loads were allowed to settle for a minimum of 5 minutes. In contrast, the XSENSOR® showed a 2% accuracy error using the Hadcock (2002) model under the same test conditions on the shoulder model. When settle time was decreased to 2-minutes, the accuracy error, in terms of vertical force, increased to 33% for the XSENSOR® and decreased to 27% for the F-Scan®, indicating a need to develop correction algorithms in each software. Further, using the hip model, the XSENSOR® showed a 4% accuracy error which is notably smaller than the 53% accuracy error from the F-Scan® system, found during the original development of the Hadcock (2002) model on the hip. Given the accuracy results, the XSENSOR® appeared to be a superior system in terms of accurately and repeatability for measuring applied forces that are allowed to settle for greater than five minutes for static conditions on curved surfaces.

## Conclusions

In conclusion, the Hadcock (2002) model is a valid method for resolving vectors into normal forces on curved surfaces. On the shoulder model, the XSENSOR® was shown to be more accurate then the F-Scan® when loads were allowed to settle for a minimum of 5 minutes. However, the XSENSOR® is currently not recommended for short 2-minute duration loading measurements on a curved surface, due to degraded accuracy at the current state of the technology. Further, the XSENSOR® was shown to have excellent accuracy compared to the F-Scan® system during hip model testing. Both systems showed a fair degree of variability for test-retest measures. This means that at least 3-4 trials should be taken to have confidence in the data. The F-Scan® system is limited in that load carriage pressures are often at the lower end of their range. In addition, the mylar sensor material is not compliant and suited to the surface of the person. On the other hand, XSENSOR® has a problem with creep, a long settling time and trial-by-trial variability. Results from this study suggest that the XSENSOR® has a better potential for use on human soldiers, although more testing is required to develop software algorithms for improved repeatability and accuracy during short duration loading applications, such as on curved surfaces or under conditions of dynamic loading.

# Sommaire


## Introduction

Pour comprendre comment l'organisme des soldats réagit à la pression causée par leur système de transport de charge personnel, les outils de mesure de pression doivent pouvoir mesurer avec justesse et de façon répétable les pressions exercées sur les surfaces incurvées du dos et des épaules. Cependant, la justesse et la répétabilité de mesure des systèmes de détection de pression modernes utilisés sur des géométries incurvées complexes, telles que l'épaule et la hanche humaines sont actuellement inconnues. Un des problèmes majeurs de la mesure des forces s'exerçant dans des zones à surface incurvée est que les vecteurs des forces ne peuvent pas être comparés, à moins d'être convertis en forces dans les plans vertical et horizontal. Pour mieux comprendre les performances des systèmes de mesure de pressions exercées sur des surfaces incurvées, deux capteurs de pression modernes (le F-Scan® et le XSENSOR®) ont été essayés sur des géométries incurvées simplifiées, y compris un modèle d'épaule cylindrique et un modèle de hanche elliptique de taille humaine.

## Méthodes

Un modèle mathématique, développé par Hadcock (2002) à partir de la technologie de mesure de la pression du F-Scan® pour convertir les vecteurs de force normaux autour d'une courbe en forces verticales et horizontales, a été validé par la comparaison des forces verticales mesurées, collectées par les capteurs XSENSOR® et F-Scan®, avec les charges réelles appliquées sur une simple sangle de sac à dos. Les gabarits d'essai utilisés dans cette étude étaient une forme sphérique représentant l'épaule et une forme elliptique représentant les hanches. Les modèles de hanche et de taille ont été validés à l'aide d'une masse fixe de 9,8 kg, et la répétabilité a été vérifiée au moyen de charges de 9,8 kg, de 14,4 kg et de 19,0 kg tant avec les tampons capteurs F-Scan® qu'avec les tampons capteurs XSENSOR®. Les données de sortie du système de mesure de pression ont ensuite été comparées avec les charges réelles appliquées par l'intermédiaire de la sangle du sac à dos pour déterminer la justesse de chaque système de mesure de pression pour les modèles d'épaule cylindrique et de hanche elliptique. En outre, la répétabilité de mesure des deux systèmes a été examinée pour le modèle d'épaule au moyen de trois charges.

## Résultats et discussion

Les résultats de l'utilisation de la méthode de Hadcock (2002) pour convertir les vecteurs de force en forces normales ont révélé que le F-Scan® avait une erreur de justesse moyenne de 72 % pour le modèle d'épaule lorsque les charges appliquées connues étaient permises de se stabiliser pendant un minimum de 5 minutes. Par contre, le XSENSOR® présentait une erreur de justesse de 2 % avec l'utilisation du modèle de Hadcock (2002) dans

les mêmes conditions d'essai pour le modèle d'épaule. Lorsque le temps de stabilisation était ramené à 2 minutes, l'erreur de justesse, en termes de force verticale, montait à 33 % pour le XSENSOR® et tombait à 27 % pour le F-Scan®, ce qui indique le besoin d'élaborer des algorithmes de correction dans chaque logiciel. En outre, dans le cas du modèle de hanche, le XSENSOR® présentait une erreur de justesse de 4 %, ce qui est nettement moins que l'erreur de justesse de 53 % du capteur F-Scan®, relevée pendant l'élaboration originale du modèle de Hadcock (2002) pour la hanche. Compte tenu des résultats de justesse, le XSENSOR® semblait être un appareil supérieur en termes de justesse et de répétabilité de la mesure de forces appliquées permises de se stabiliser pendant plus de cinq minutes dans des conditions statiques sur des surfaces incurvées.

**Conclusions**

En conclusion, on peut affirmer que le modèle de Hadcock (2002) correspond à une méthode valide de convertir des vecteurs en forces normales sur des surfaces incurvées. Dans le cas du modèle d'épaule, le XSENSOR® s'est avéré plus précis que le F-Scan® lorsque les charges étaient permises de se stabiliser pendant au moins 5 minutes. Toutefois, à l'heure actuelle, le XSENSOR® n'est pas recommandé pour les mesures de charges de 2 minutes de durée sur une surface incurvée, à cause de la justesse dégradée à l'état actuel de la technologie. De plus, on a démontré que le XSENSOR® a une excellente justesse comparativement au F-Scan® pendant les essais sur le modèle de hanche. Les deux systèmes présentaient un certain degré de variation aux mesures de répétabilité. Cela veut dire qu'il faut prendre au moins 3-4 mesures avant de pouvoir se fier aux données. Le capteur F-Scan® est limité dans la mesure où les pressions de transport de charge se trouvent souvent à la limite inférieure de sa gamme de mesure. De plus, le matériau des capteurs, le mylar, n'est pas souple et ne convient pas à la surface d'une personne. Par contre, le XSENSOR® a un problème de fluage, un temps de stabilisation prolongé et une variabilité d'un essai à l'autre. Les résultats de cette étude semblent indiquer que le XSENSOR® a un meilleur potentiel d'application sur les soldats, mais il faut d'autres essais pour élaborer des algorithmes logiciels aux fins d'une répétabilité et d'une justesse améliorées dans des applications de charge de courte durée, telles que sur des surfaces incurvées ou dans des conditions de charge dynamique.

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# 1.0 Introduction

Modern pressure measurement systems are small, portable and flexible so they can be used to study contact pressure between varieties of surfaces. However, the accuracy and repeatability of such systems when measuring forces on curved surfaces are poorly understood. To study the complex nature of the backpack-person pressure interface for a soldier wearing a personal load carriage system, measurements must account for the various forces being applied to the complex geometries of the torso and shoulders. Previous DRDC reports have investigated a number of pressure systems on simple geometries such as static flat loaded conditions and dynamic flat loaded conditions (Fergenbaum *et al.*, 2003a; Fergenbaum *et al.*, 2003b; Morin *et al.*, 2003). Before pressure systems can be used with confidence to study forces applied to complex geometries such as the torso or shoulders, controlled studies of pressure measurement systems should first focus on sensor performance when used on simplified curved models of the shoulder and torso.

# 2.0 Purpose

The goal of this research was to evaluate two currently available pressure-sensing technologies on static curved surfaces using a standardized shoulder and hip model. The purpose was to determine whether the systems would be appropriate to study the relationship between load carriage and pressure tolerance limits in soldiers.

# 3.0 Literature Review

Problems concerning use of pressure measurement systems on curved surfaces have been known for some time, such as reduced sensor output on curves (Buis and Convery, 1997), increased inaccuracy from mild bending (Morin et al. 1998), and a need for a calibration method for curved surfaces (MacNeil 1996). Research to resolve these challenges have been scarce to date, particularly with particular relevance to personal load carriage equipment. Further, recent advances in pressure sensing technology, such as the FSA Vista Medical System (FSA) and the XSENSOR® compliant sensor mats, have made measurement of pressure on curved surfaces more practical. Recent DRDC reports have tested these systems on flat surfaces (Fergenbaum *et al.*, 2003a; Fergenbaum *et al.*, 2003b; Morin *et al.*, 2003). Morin *et al.* (2003) investigated the measurement bias of the FSA, the F-Scan® and XSENSOR® systems under standardized static loading on flat surfaces and Fergenbaum *et al.* (2003a) focused on testing the FSA, the F-Scan® and XSENSOR® for accuracy, repeatability, creep and low threshold sensitivity on flat surfaces; as well as the dynamic accuracy and repeatability of the FSA and XSENSOR® systems (Fergenbaum *et al.*, 2003b). From these reports, XSENSOR® was found to be more accurate and sensitive at low thresholds than the FSA and F-Scan® systems under controlled static, flat loaded conditions. The XSENSOR®

system also demonstrated better repeatability under these test conditions. The dynamic response of these systems on curved surfaces has yet to be investigated to date.

Previous work by Holewijn (1990) examined pressures applied on the curved surface of the shoulder area. He developed a mathematical model to convert pressure on the shoulder into vertical force to calculate strap forces. Pressures were measured at 5 positions and it was assumed that the shoulder was cylindrical with a radius of 50 mm. The cylinder was treated as frictionless and only the superior sections of the shoulder significantly contributed to the vertical force. Calculations of lower strap forces indicated that some of the load for a customized backpack was transferred to the hips, although the model was not validated. Without validation, the application of this model for pressure measurements is limited. In fact, McPoil *et al.* (1995) cautioned about the validity of pressure sensors used in contoured environments, particularly with relevance to pressure insoles. McPoil *et al.* (1995) stated that vertical ground reaction forces can be measured accurately with a force platform, but not with pressure insoles. They argued that pressure pad insoles only measured normal forces, not true vertical forces, and these do not represent vertical forces, because of the foot orientation to the ground, particularly during the initial and late portions of the walking cycle. They further questioned clinical usefulness of an insole pressure sensor placed over a foot orthotic since the curvature of the orthotic changes the direction of the measured force vector confounding the interpretation of pressure results. However, in their paper McPoil *et al.* (1995) did not propose a solution.

Others have also cautioned about the practical use and interpretation of pressure sensors on curved surfaces. Bain (1997) examined the effects of a Tally Pneumatic transducer loaded with a spherical dome having radii between 19-87 mm and reported that curvature had large influences on the output, affecting the accuracy of the transducer. Further, Buis and Convery (1997) reported that spherical curvatures introduced significant reductions in the outputs using F-Scan® model #9810 resistors by Tekscan Inc. (307 West First Street, South Boston, MA 02127-1309). Recently, Ferguson-Pell (2000) tested a low pressure detection sensor (FlexiForce® by Tekscan) on curved surface with radii of curvature between 8.0 to 51.7 mm. Results showed that a radius of curvature of less than 32 mm reported a pressure when no load was placed on the sensor.

Despite the problems associated with pressure measurement on a curved surface, some researchers have attempted to offer a solution. MacNeil (1996) developed and validated a method to measure pressure around a curved shoulder model using the Tekscan (F-Scan®) pressure measurement system. This model was used to evaluate the backpack-human interface for the Canadian Armed Forces. Two different straps were wrapped around a symmetrical tube (d = 114 mm) covered with Bocklite™ (Otto Bock Orthopedic Industry of Canada Ltd., 2897 Brighton Road, Oakville, ON L6H 6C9) cushioning to simulate human tissue compliance over bone. Known masses were suspended by the strap from one side of the tube while strap tensions and pressure measurements were recorded. Strap tensions were measured using a custom force transducer developed in a previous study. It was found that the F-Scan® sensor measured forces 8.7% higher than those predicted by shoulder reaction force calculations. A model that incorporated friction was successfully developed and validated to offset the 8.7% bias and more accurately predict strap tension based on the pulley equation to account for the unequal forces. However, the author acknowledged that a significant limitation to the model was that backpack waist strap forces were not considered, and that there was no existing method to properly calibrate the F-Scan® system on a curved surface.

Expanding on work by MacNeil, Hadcock (2002) developed a method to calculate waist strap forces and developed an *in situ* technique to calibrate a Tekscan (F-Scan®) pressure measurement system. An elliptical human-sized lower torso model was created of wood and covered with Bocklite™ cushioning. Tekscan (F-Scan®) sensors, comprised of 96 individual sensels were used to measure the surface pressures between the torso and a waist belt. Three dimensional vectors for the applied force on each individual sensel (sensel) were resolved and using selected sites on the waist belt, known external forces were applied and compared to the measured forces summed over the pressure array. The method was used to calibrate the sensors *in situ*, across the measurement range of interest and resulted in an accuracy of the system to within 19% of a known applied force.

The purpose of this study was to apply these techniques to more complex geometries to determine whether suitable accuracy could be achieved for load carriage studies using currently available pressure sensing technology.

# 4.0 Methods

Two different pressure sensing systems were tested, a capacitance system and a resistive ink system. The capacitance technology tested was the X2 seat system, manufactured by XSENSOR® Technology Corporation. The pad was constructed of a pliable urethane plastic material which could be easily detached from its electronics. XSENSOR® provides a portable acquisition mode using a smart media card or online through high speed USB. Testing was done using the online USB option. The sensor pad model tested was an X36 seat pad, referring to a 36 by 36 individual sensor arrangement, measuring 457.2 mm by 457.2 mm with a pad thickness of less than 1 mm. The sensor pad was composed of 1296 individual capacitive sensors and the software was programmed to scan the sensors at 1 Hz. The system was newly calibrated by the manufacturer for the pressure range between 1.3 - 26.7 kPa (10-200 mmHg).

The resistive ink technology tested was the F-Scan® (F-socket series) model, manufactured by Tekscan Incorporated. It was constructed of a thin (0.18 mm thick) flexible, printed ink circuit that was detachable from its electronics. The software tested was Version 4.21 with an associated 9811 sensor pad. The sensing region measured 203 mm by 76 mm and was composed of 96 individual sensors in total. The software was programmed to sample the pad at 1 Hz. The manufacturer recommended an operating range is between 0 - 241.3 kPa (0 – 1810 mmHg). The system was newly calibrated in the laboratory using a custom-made air

bladder calibration system. Detailed set-up and methods of data extraction are outlined in appendix C.
The experimental design consisted of three steps (See Figure 1). Two were undertaken using a physical model for the shoulder in order to estimate the effects of duration of loading. A long duration test was first performed to verify the accuracy of the vector resolution method. Next, a short duration test was used to determine the performance of the systems given less response time during loading. In the third step of the study, a physical model of the hip was used with an appropriate response time determined from the first two experiments.

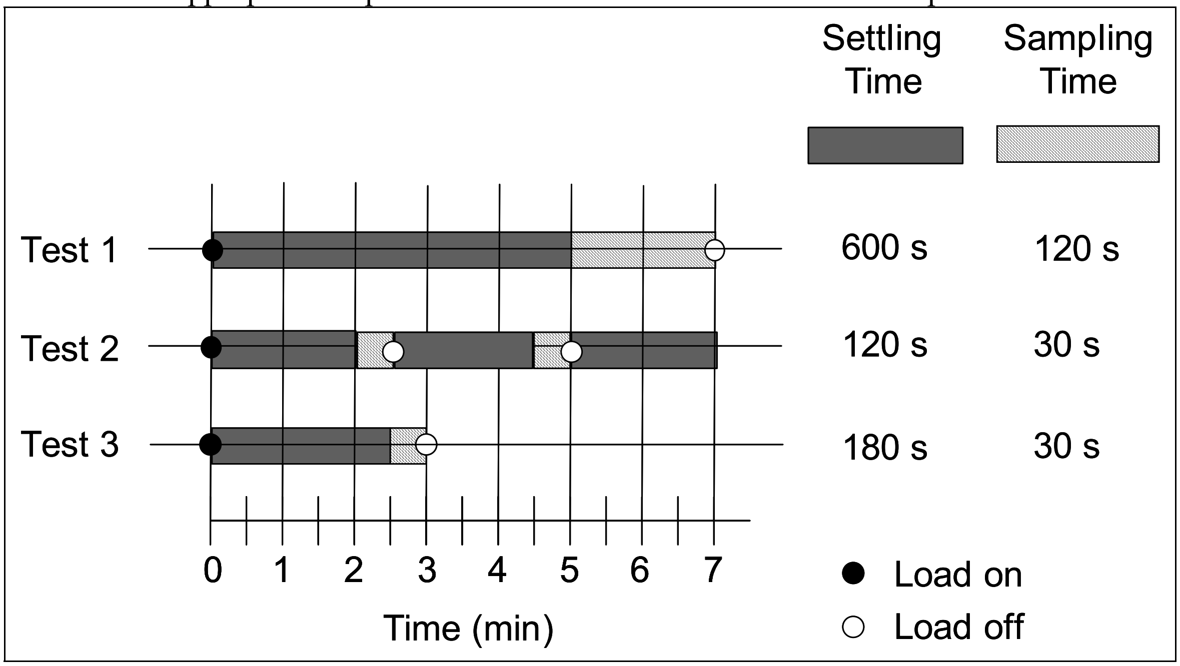


Figure 1. Schematic of test protocols for static shoulder and hip tests.

## 4.1 Shoulder Testing

### 4.1.1 Protocol

A 3 mm Bocklite™ foam sheet was glued to a PVC cylinder (diameter = 114 mm, wall thickness = 6 mm). The XSENSOR® and F-Scan® pressure pads were placed over the Bocklite™ layer and fixed in position with single-sided utility box tape. A 49 mm wide strap was placed over the sensor pad and the contact area of the strap-sensor interface marked with white tape to ensure that the same sensors were loaded in the same area. Accuracy of the strap location was checked using output from the pressure system to verify the loading pattern.

A 0.41 kg fixture was suspended from the straps to support the loads used in the protocols as shown in Figure 2. All loads were placed in the fixture and levelled at the start of each trial. Before all testing, the maximum load was placed on the sensors and the software checked to ensure that applied loads were within in the sensor's calibration range. This protocol was repeated for both the F-Scan® and XSENSOR® systems.

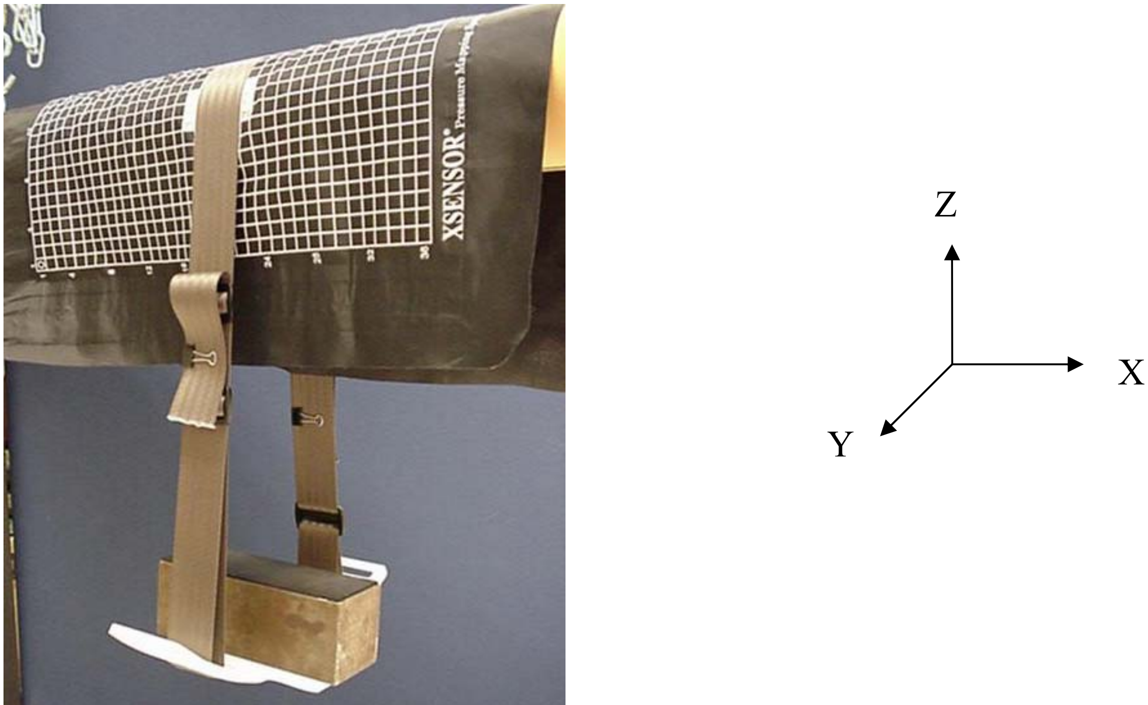


Figure 2. Set up for Shoulder Model Testing using the XSENSOR®.

### 4.1.2 Static Analysis

As shown in Figure 3, the expected total vertical force was due to the weight ($F = mg$) for each loaded condition. To calculate the overall vertical force measured by each pressure sensing system, the vertical force acting on each individual sensor was calculated first, then all of the individual vertical forces summed to determine the total vertical force measured by the system. To calculate the individual vertical force acting on a sensel, first the separation of each sensel, $d\varphi$, is determined such that $d\varphi = 180/n$ deg where n is the number of individual sensors in contact with the top half of the circular tube. Using the coordinate system shown in Figure 3, the angle of force vector, $\varphi_i$, for each sensel, *i*, is given by $\varphi_i = (2i - 1)\, d\varphi /2$.

The force on each sensel, $F_i$, is given by the reported pressure, $p_i$, and the manufacturer stated sensel area $A_o$ such that $F_i = p_i A_o$. For both systems $A_o = 161$ mm$^2$ (0.25 in$^2$).

The vertical component of $F_i$ is given by $Fv_i = F_i \sin \varphi_i$, and the horizontal component given by $Fh_i = F_i \cos \varphi_i$, as shown in Figure 2d. Summing over the sensors:
$\Sigma Fv_i = F$ or $\Sigma F_i \sin \varphi_i = mg$
and $\Sigma Fh_i = 0$ or $\Sigma F_i \cos \varphi_i = 0$.

As such, the summed horizontal forces should equal zero and the summed vertical forces equal the applied weight.

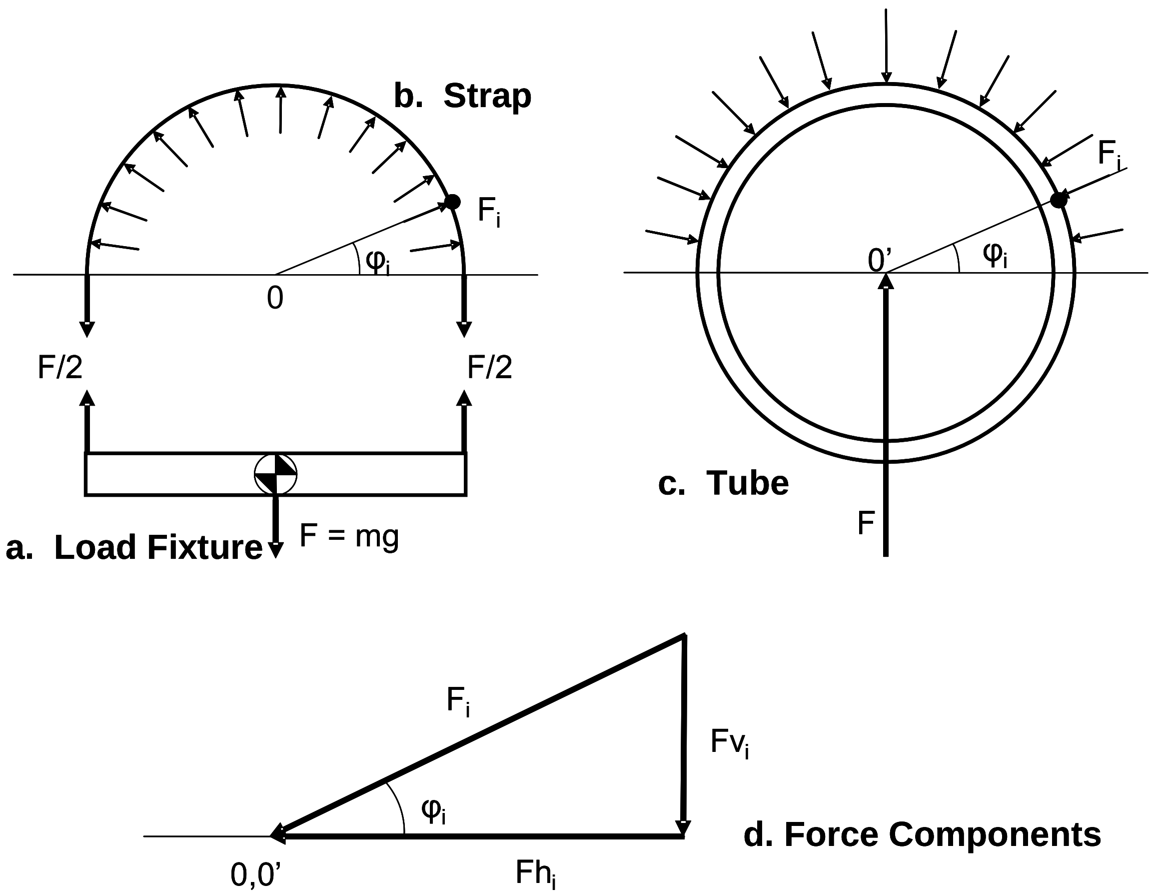


Figure 3. Loading on strap and tube during testing.

A) The load fixture is attached to the tube by two ends of the strap. The total load is assumed to be equally distributed to each side. B) The normal force at each sensel, $F_i$, acts on the inside of the strap. Friction forces are assumed to be negligible. C). The normal forces on the tube are sensed by the pressure array and respond as pressures acting over a sensel area. D). $F_i$ is resolved into vertical and horizontal components such that $Fv_i = F_i \sin \varphi_i$ and $Fh_i = F_i \cos \varphi_i$. Note that the total vertical force is equal to the applied weight, F, and the total horizontal force should equal zero.

### 4.1.3 Long Duration Testing

A 9.84 kg mass (fixture included) was suspended from the shoulder model for five minutes to allow settling, followed by two minutes of data collection by the pressure measurement system at 1 Hz. Equipment was unloaded from the sensor and the loading procedure was repeated for a total of three trials to obtain consistent data similar to Hadcock, (2002). For analysis, only the middle 50% of the samples collected were used for statistical analysis to ensure best results between unloaded and loaded conditions. All data were analyzed using MS Office XP software in EXCEL® (Appendix D).

### 4.1.4 Incremental Loading

This protocol was used to determine the accuracy and repeatability of various loads in the calibrated range. Masses (including the fixture) of 9.8 kg, 14.4 kg, and a 19.0 kg were suspended from the shoulder model. Each load was sampled by each pressure measurement system at 1 Hz for a two minute interval, unloaded for 30 seconds, and then loaded for a 2-minute re-test. The middle 50% of the samples collected were used for statistical analysis.

Data from loaded trials were normalized by calculating the vertical force (z-direction) reported by the pressure system and then dividing this measured force by the actual force applied by the suspended mass. Mean pressures were also calculated for each load condition. All data were analyzed using MS Office XP software in an EXCEL® spreadsheet (see example in Appendix D).

## 4.2 Hip Testing

The hip data were collected at two different times using the same protocol. The F-Scan data was previously reported by Hadcock et al (2002b) under contract W7711-0-7632-02. The XSENSOR data have been collected within this contract. A summary of the detailed protocol will be provided here for ease of comprehension.

An elliptical human-sized Simulated Lower Torso (SLT) model was created of wood and covered with 3 - mm thick Bocklite™ sheet. The XSENSOR® pad was placed over the Bocklite™ and fixed in position with tape as shown in Figure 4. A 49 mm wide strap was placed over the sensor pad and the contact area of the strap-sensor interface was marked with white tape to ensure that the same sensors were loaded in the same area to maintain testing consistency between trials. Further, the strap location was checked to ensure that the strap was placed on the sensor pad in a location that would ensure that each individual sensor was covered fully and which loaded evenly during testing. In addition, a 49 mm wide foam cushion (8 mm thick) was placed between the strap and the pressure sensor to load the sensors more evenly. The angle of the webbing corresponded to the slope of the SLT in order to maximize contact with the sensor and provide a normal force to the surface (Figure 5). A spreader bar was inserted between the SLT and the gauge to hold the strap out from the sides of the SLT as contact on only one sensor on a hip was being tested. This spreader bar did not change the external forces acting on the system as demonstrated by Hadcock (2002).

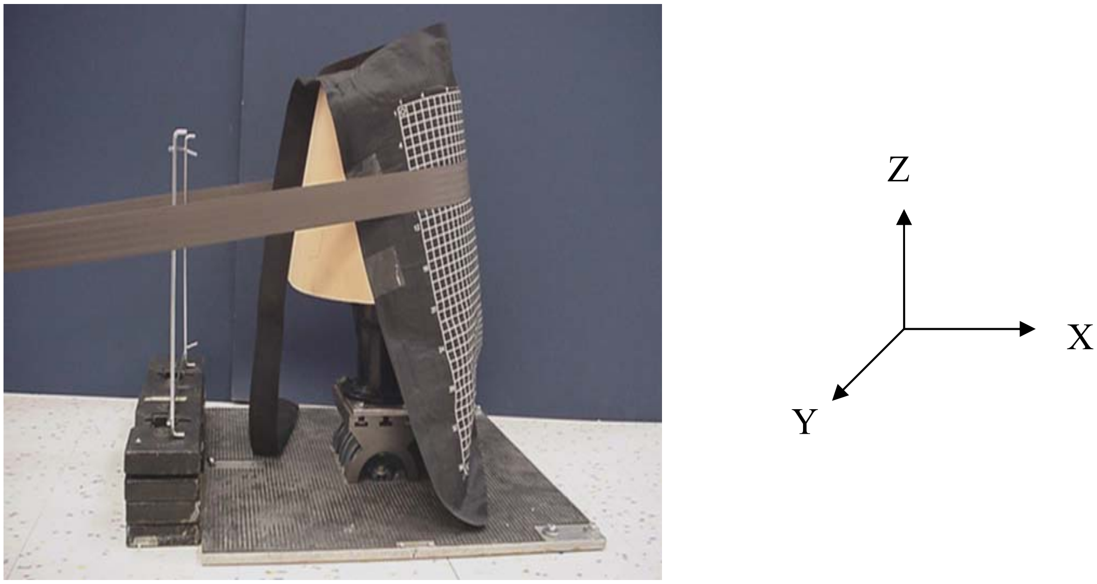


Figure 4. Set up for Hip Model Testing using the XSENSOR® pad.

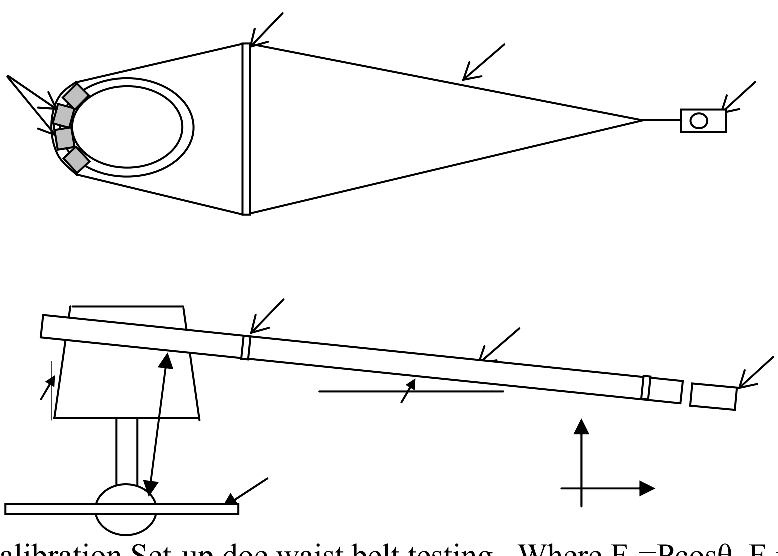

Figure 5. Calibration Set-up doe waist belt testing . Where $F_x$=Pcosθ, $F_z$=-Psinθ, and $M_y$=Pd.

The ends of the strap were fixed to one end of a Shimpo® MF-100 force gauge. The opposite end of the force gauge was fixed to a mechanical hoist that was moved toward or away from the model hip to decrease or increase, respectively, the tension in the strap. When a given strap tension was reached, the strap force was allowed to settle on the sensor for a 3-minute interval. In the first minute of every trial, the strap was adjusted manually by the experimenter to evenly distribute the force over each individual sensor. The last 30 seconds of data from each trial were used for analysis.

Since the elliptical sides of the lower torso were at an angle of 10 degrees from the vertical, a 10 degree strap angle from the horizontal created an applied load perpendicular to the torso. The methodology for the resolution of forces in three dimensions for this hip model follows the general principles used for vertical forces in the simpler geometry of the tube and is described in detail in Hadcock (2002). Data from loaded trials were normalized by calculating the normal horizontal force (z-direction) reported by the pressure system and then dividing this measured force by the actual force (in Newtons) applied by the external loading apparatus. All directional force coordinates were analyzed using MS Office XP software in an EXCEL® spreadsheet (Appendix E).

# 5.0 Results

## 5.1 Shoulder Testing

### 5.1.1 Static Tests

Table 1 provides a summary of three trials measured by the F-Scan® and XSENSOR® technologies. Raw statistical data analyzed using SPSS version 9.0 is summarized in Appendix A. F-Scan® had greater variability trial-by-trial as reflected in the coefficient of variation with 15.7% for Fz vertical force. In contrast, the XSENSOR® had less variability trial-by-trial as reflected in a 0.5% coefficient of variability for the Fz vertical force. When the measured vertical force (Fz value) was calculated and results were normalized against the applied load, F-Scan showed a normalized value of 1.72, overestimating the load by 72%. Data for the XSENSOR® demonstrated a normalized value of 0.98, indicating that XSENSOR® underestimated the applied load by 2%.

Table 1. Results of static loading. Vertical (Fz) and horizontal (Fx) forces calculated based on these trials at 10 kg.

| ***Outcome Measure*** | ***XSENSOR®*** | | ***F-Scan®*** | |
|---|---|---|---|---|
| | ***Fz*** | ***Fx*** | ***Fz*** | ***Fx*** |
| Measured Trial 1 [N] | 95.1 | -0.5 | 137.3 | 4.3 |
| Measured Trial 2 [N] | 95.3 | 1.5 | 188.3 | 2.2 |
| Measured Trial 3 [N] | 94.3 | 1.1 | 170.6 | 4.7 |
| Mean (STD) [N] | 94.9 (0.52) | 0.70 (1.05) | 165.73 (25.90) | 3.7 (1.37) |
| Coefficient of variance | 0.01 | 1.49 | 0.16 | 0.37 |
| Expected Load [N] | 96.5 | 0 | 96.5 | 0 |
| Normalized to Expected | 0.98 | - | 1.72 | - |

### 5.1.2 Incremental Loading

Table, 2 and 3, provide results of the incremental loading experiments from the XSENSOR® and F-Scan®. For XSENSOR®, the average normalized value for the vertical force (Fz) was 0.67 (ranged 0.61 to 0.75). Therefore, the XSENSOR® underestimated actual loads by 25% to 39% overall (Table 2). For the F-Scan®, the average normalized value for the vertical was 0.73 (range 0.65 to 0.83). This system underestimated the actual loads by 17% to 35% overall (Table 3). Both systems reported net forces in the x – direction (XSENSOR® = 26.7N - 47.2 N; F-Scan® = 14.5 N - 24 N) compared to the reported value of zero. The values should mathematically add to zero since the right and left sides of the cylindrical shape should cancel each other.

Table 2. XSENSOR® Resolved Normal Forces on the shoulder model in Incremental loading test.

| Step | Vertical Force Measured Fz (N) | Vertical Force Predicted Fz (N) | Vertical Force Normalized Fz | Horizontal Force Measured Fx (N) | Horizontal Force Predicted Fx (N) | Mean Errors Fz (N) | Mean Errors Fx (N) |
|---|---|---|---|---|---|---|---|
| 1 | 64.6 | 96.1 | 0.67 | 26.7 | 0 | 31.5 | 26.7 |
| 2 | 66.4 | 96.1 | 0.69 | 26.6 | 0 | 29.7 | 26.6 |
| 3 | 94.1 | 141.2 | 0.67 | 39.9 | 0 | 47.2 | 39.9 |
| 4 | 106.5 | 141.2 | 0.75 | 40.8 | 0 | 34.8 | 40.8 |
| 5 | 115.4 | 186.7 | 0.62 | 45.7 | 0 | 71.3 | 45.7 |
| 6 | 117.6 | 186.7 | 0.61 | 47.2 | 0 | 69.1 | 47.2 |
| ***Average*** | | | ***0.67*** | | | ***47.3*** | ***37.8*** |
| ***Standard Deviation*** | | | ***0.05*** | | | ***17.15*** | ***8.27*** |

Table 3. F-Scan® Resolved Normal Forces on the shoulder model in Incremental loading test.

| Step | Vertical Force Measured Fz (N) | Vertical Force Predicted Fz (N) | Vertical Force Normalized Fz | Horizontal Force Measured Fx (N) | Horizontal Force Predicted Fx (N) | Mean Errors Fz (N) | Mean Errors Fx (N) |
|---|---|---|---|---|---|---|---|
| 1 | 80.1 | 96.1 | 0.83 | 21.9 | 0 | 16.0 | 21.9 |
| 2 | 75.8 | 96.1 | 0.79 | 17.8 | 0 | 20.3 | 17.8 |
| 3 | 117.1 | 141.2 | 0.83 | 24.0 | 0 | 24.1 | 24.0 |
| 4 | 105.0 | 141.2 | 0.74 | 31.5 | 0 | 36.2 | 31.5 |
| 5 | 121.2 | 186.7 | 0.65 | 14.5 | 0 | 65.5 | 14.5 |
| 6 | 121.2 | 186.7 | 0.65 | 16.5 | 0 | 65.5 | 16.5 |
| ***Average*** | | | ***0.73*** | | | ***38.0*** | ***21.0*** |
| ***Standard Deviation*** | | | ***0.08*** | | | ***20.42*** | ***5.67*** |

Figure 6 shows a typical output data collected during incremental loading for a single sensel in the XSENSOR® pad. Pressure values generally tended to increase with time and increase with sequential loads. The data are summarized in Table 4 averaged over all sensels for XSENSOR®. The coefficient of variance based on the mean pressures, ranged from 0.003 to 0.018 (0.3% to 1.8%) with an overall average of 0.9% for each load. For the F-Scan® (Table 5) the coefficient of variation, based on the deviations of mean pressures, ranged from 0.0015 to 0.003 or 0.15% to 0.3% with an overall average coefficient of variance of 0.21% for each load. The results show a relatively stable and repeatable relationship for both systems.

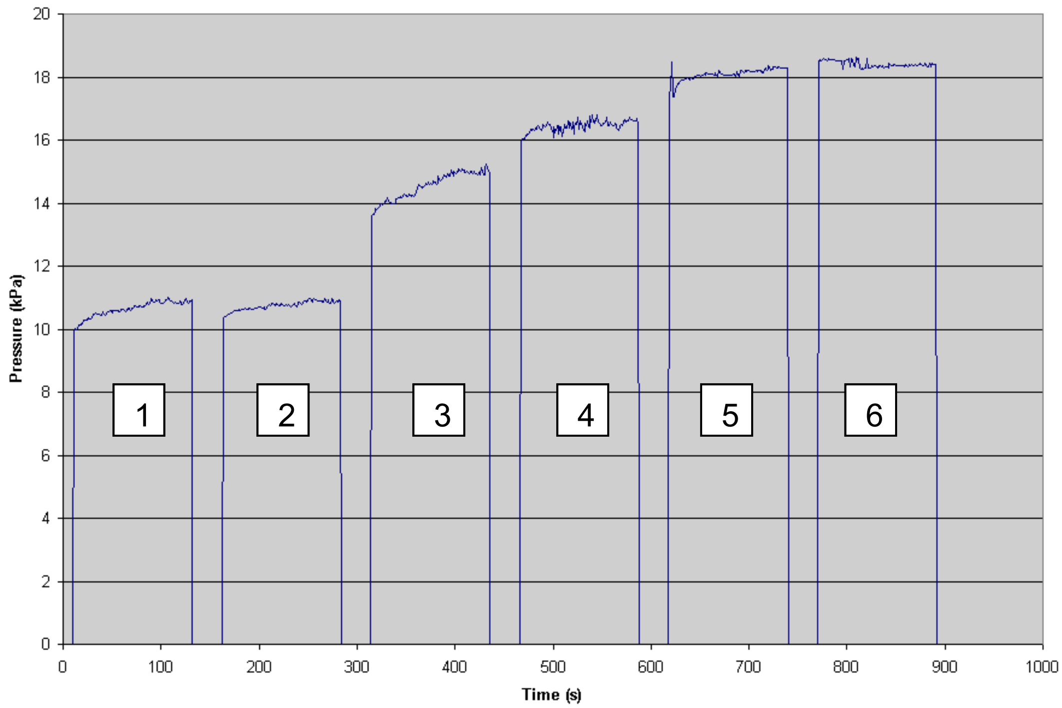


Figure 6. Data Collected using the XSENSOR® pad during Test-retest Conditions.

Steps 1 and 2 used 9.8 kg, Steps 3 and 4 used 14.4 kg, and Steps 5 and 6 used 19.0 kg masses for the Shoulder Model.

Table 4. XSENSOR® Means and Standard for Steps one through six during Test-retest Conditions for the Shoulder Model.

| Step | Mean Pressure (kPa) | Standard Deviation (kPa) | Coefficient of Variation |
|---|---|---|---|
| 1 | 10.7 | 0.13 | 0.012 |
| 2 | 10.8 | 0.08 | 0.007 |
| 3 | 14.6 | 0.26 | 0.018 |
| 4 | 16.5 | 0.15 | 0.009 |
| 5 | 18.1 | 0.06 | 0.003 |
| 6 | 18.4 | 0.10 | 0.006 |
| ***Average*** | | | ***0.009*** |

Table 5. F-Scan® Means and Standard for Steps one through six during Test-retest Conditions for the Shoulder Model.

| Step | Mean Pressure (kPa) | Standard Deviation (kPa) | Coefficient of Variation |
|---|---|---|---|
| 1 | 10.7 | 0.11 | 0.010 |
| 2 | 10.0 | 0.11 | 0.011 |
| 3 | 13.2 | 0.11 | 0.008 |
| 4 | 12.1 | 0.10 | 0.008 |
| 5 | 17.7 | 0.25 | 0.014 |
| 6 | 19.9 | 0.27 | 0.014 |
| ***Average*** | | | ***0.011*** |

## 5.2 Hip Testing

Table 6 summarizes normal forces in the horizontal plane (Fx), the vertical plane (Fz) and the anterior-posterior plane (Fy). The average measured force in the vertical plane was 82.59 N in comparison to an expected value of 88.62 N. The expected force in the anterior-posterior (Fy) plane was -.221 N compared to an expected value of zero. The average normalized value for all ten trials in the horizontal plane was 0.960 indicating that the XSENSOR® underestimated the actual applied load by 4%. Given the range of normalized data in the horizontal plane (0.822 to 1.046), the accuracy error associated with the XSENSOR® ranged from a 17.8% underestimation of the actual load applied to a 4.6% overestimation of the applied load. The results from hip testing using the F-Scan® system, extracted from Hadcock

(2002) and DRDC technical report w7711-0-7632-02 (Hadcock, 2002a) are shown in Appendix B.

Table 6. XSENSOR® Resolved Normal Forces on hip model in static loading.

| *Trial Number* | *Measured Force (N)* | | | *Expected Force (N)* | | | *Normalized Force* | | *Errors (N)* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Fx* | *Fy* | *Fz* | *Fx* | *Fy* | *Fz* | *Fx* | *Fz* | *Fx* | *Fy* | *Fz* |
| 1 | 184.5 | 4.6 | -35.5 | 224.5 | 0 | -39.59 | 0.82 | 0.90 | 40.02 | -4.55 | -4.12 |
| 2 | 127.0 | -4.3 | -23.9 | 136.9 | 0 | -24.14 | 0.93 | 0.99 | 9.90 | 4.33 | -0.21 |
| 3 | 105.7 | -3.8 | -19.9 | 109.1 | 0 | -19.23 | 0.97 | 1.03 | 3.39 | 3.84 | 0.65 |
| 4 | 89.6 | -2.4 | -16.9 | 91.6 | 0 | -16.14 | 0.98 | 1.04 | 1.95 | 2.40 | 0.71 |
| 5 | 74.1 | -2.5 | -14.0 | 75.8 | 0 | -13.36 | 0.98 | 1.05 | 1.66 | 2.53 | 0.65 |
| 6 | 59.8 | 1.3 | -11.4 | 60.0 | 0 | -10.58 | 1.00 | 1.07 | 0.19 | -1.30 | 0.79 |
| 7 | 51.8 | 1.4 | -10.0 | 53.4 | 0 | -9.42 | 0.97 | 1.06 | 1.66 | -1.36 | 0.53 |
| 8 | 49.2 | 1.2 | -9.4 | 48.2 | 0 | -8.50 | 1.02 | 1.10 | -1.00 | -1.17 | 0.88 |
| 9 | 45.8 | 0.7 | -8.7 | 43.8 | 0 | -7.72 | 1.05 | 1.12 | -2.00 | -0.74 | 0.96 |
| 10 | 38.4 | 1.8 | -7.3 | 42.9 | 0 | -7.57 | 0.89 | 0.96 | 4.57 | -1.76 | -0.28 |
| ***Mean*** | | | | | | | ***0.96*** | ***1.03*** | ***6.03*** | ***0.22*** | ***0.06*** |
| ***Standard Deviation*** | | | | | | | ***0.06*** | ***0.07*** | ***3.52*** | ***2.88*** | ***1.53*** |
| ***Standard Error of the Mean*** | | | | | | | ***0.02*** | ***0.02*** | ***3.92*** | ***0.91*** | ***0.48*** |

Table 7. F-Scan® Resolved Normal Forces on hip model in static loading.

| *Trial Number* | *Measured Force (N)* | | | *Expected Force (N)* | | | *Normalized Force* | | *Errors (N)* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Fx* | *Fy* | *Fz* | *Fx* | *Fy* | *Fz* | *Fx* | *Fz* | *Fx* | *Fy* | *Fz* |
| 1 | 40.4 | -3.5 | 6.9 | 90.5 | 0 | 12.7 | 0.45 | 0.54 | 50.1 | 3.5 | 5.8 |
| 2 | 35.2 | -4.7 | 6.2 | 86.5 | 0 | 12.2 | 0.41 | 0.51 | 51.3 | 4.7 | 6.0 |
| 3 | 61.7 | -7.1 | 10.5 | 118.3 | 0 | 16.6 | 0.52 | 0.63 | 56.6 | 7.1 | 6.1 |
| 4 | 28.2 | 1.1 | 5.0 | 68.0 | 0 | 9.6 | 0.41 | 0.52 | 39.8 | -1.1 | 4.6 |
| 5 | 29.0 | -3.8 | 5.2 | 71.5 | 0 | 10.1 | 0.41 | 0.51 | 42.5 | 3.8 | 4.9 |
| 6 | 35.7 | -3.2 | 6.2 | 84.8 | 0 | 11.9 | 0.42 | 0.52 | 49.1 | 3.2 | 5.7 |
| 7 | 48.6 | -4.7 | 8.3 | 103.3 | 0 | 14.5 | 0.47 | 0.57 | 54.7 | 4.7 | 6.2 |
| 8 | 44.6 | -5.3 | 7.8 | 102.7 | 0 | 14.4 | 0.43 | 0.54 | 58.1 | 5.3 | 6.6 |
| 9 | 37.0 | -1.5 | 6.2 | 67.1 | 0 | 9.4 | 0.55 | 0.66 | 30.1 | 1.5 | 3.2 |
| 10 | 58.1 | -2.6 | 9.6 | 92.3 | 0 | 13.0 | 0.63 | 0.74 | 34.2 | 2.6 | 3.4 |
| 11 | 47.7 | -2.8 | 8.1 | 89.2 | 0 | 12.5 | 0.53 | 0.65 | 41.5 | 2.8 | 4.4 |
| ***Mean*** | | | | | | | ***0.48*** | ***0.58*** | ***46.18*** | ***3.46*** | ***5.17*** |
| ***Standard Deviation*** | | | | | | | ***0.07*** | ***0.08*** | ***10.09*** | ***2.14*** | ***1.16*** |
| ***Standard Error of the Mean*** | | | | | | | ***0.02*** | ***0.02*** | ***3.03*** | ***0.68*** | ***0.37*** |

# 6.0 Discussion

## 6.1 Validity of Pressure Systems

For the shoulder model, the normalized value calculated in Table 1 for the XSENSOR® shows that the mathematical model developed by Hadcock (2002) was a valid model to measure applied pressures on a curve. Using this model for the XSENSOR® was extremely accurate at measuring applied vertical load, underestimating the actual applied force by 2%. In contrast, the same mathematical model used for the F-Scan®, overestimated applied vertical force by 72%. These findings suggest that there are problems with accuracy with using the F-Scan® on curved surfaces. These finding are also consistent with others who have reported problems with Tekscan technology on a curve, with the main problem being that the system becomes active from when the sensor pad is bent around a curved surface, even when no load is applied (Buis and Convery, 1997; Ferguson-Pell 2000).

In addition, using the Hadcock (2002) mathematical model for the model hip, the XSENSOR® proved to be more accurate on an elliptical surface than the F-Scan®. In earlier work, Hadcock (2002) used the F-Scan® to develop a mathematical model to resolve normal forces on the elliptical hip surface. However, early work showed that the F-Scan® had an average accuracy error of 52.6 ± 7.2% (average normalized value of 0.47) for applied strap forces of 67.1 to 118.3 Newtons. In contrast, the same mathematical model in this study showed that the XSENSOR® had an overall 4% accuracy error measuring applied strap force between 38.36 N to 184.49 N on the elliptical surface. One reason for this difference may have been that data were being collected at the lower end of the F-Scan's® calibration range. Hadcock (2002) showed that at lease three trials has to be taken to ensure that the F-Scan® error of the mean was reduced. These findings suggest that the XSENSOR® has the greatest future potential to examine backpack pressures using standardized testing on curved surfaces; particularly since the XSENSOR® is thin, flexible technology which is less affected on circular and elliptical surfaces.

## 6.2 Reliability and Repeatability

To test for precision of the XSENSOR® on the shoulder model, the coefficient of variation was used to measure of the dispersion of data around the mean. The expected vertical force for all three trials was 96.50 N (Table 1). However, the F-Scan® reported a very inaccurate average vertical force of 165.73 ± 0.16 N over the three trials. In contrast, the XSENSOR® measured an average vertical force of 94.93 ± 0.006 N which was very consistent. Based on the coefficient of variation in Table 1, the XSENSOR® was highly reliable (0.5% variation) compared to the F-Scan® (15.6% variation) over the three identically loaded trials. These results suggest that XSENSOR® sensor is not only more accurate that the F-Scan®, but also is more reliable for measurement on a curve when a five-minute settling time was used.

Accuracy of the XSENSOR® was also tested on the shoulder using a number of loads between 96.12 N to 186.69 N (Table 2) for short two-minute durations of applied pressure; however, accuracy error was shown to increase for 2-minute loading. Based on results in Table 2, the XSENSOR® underestimated actual loads between 25-39% with an overall average error of 33% for all loaded conditions. The reason for this increase in accuracy error compared to Table 1 suggests that the current software for the XSENSOR® system is not designed to compensate for errors resulting from short duration settling of loads (i.e., less than 5 minutes). Consequently, future experimentation would be required to develop mathematical algorithms for the software to compensate for short duration loading, so that the XSENSOR® system could be used to accurately measure short duration loads.

In contrast, accuracy of the F-Scan® for the same applied pressures, showed substantially different results that the XSENSOR®, perhaps due to the differences in technology (Table 3). Based on short two-minute durations of applied pressure, results in table 3 show the F-Scan® underestimated actual loads (when compared in Newtons) between 17-35% with an overall average error of 27% for all loaded conditions. This force data appears similar to the XSENSOR® results, however, when this force is divided by the area to give a pressure (pressure = force/area), the reported pressure values increased dramatically as seen in Table 4. The reason for this dramatic increase in error when pressure is calculated is probably due to the difficulty of reading pressure at the low end of the scale.

One main challenge for the resistive ink technology on a curved surface is that the sensels cannot be loaded uniformly, even when the applied pressure is uniform. Both pressure systems are able to monitor the magnitude of pressure acting on each sensel in real time. It was noted that XSENSOR® showed a rapid, uniform settling of the load and the system was faster at identifying the rectangular shape of the uniform applied load from the strap. In contrast, F-Scan® indicated the load was unevenly activated along the top of the shoulder and irregularly applied over the sensor. The F-Scan® contact area shape did not reflect the rectangular shape of the applied load, and many of the sensels did not respond to the load during the two-minute time constraint. The F-Scan® system had a greater problem correctly identifying the contact area under these test conditions (Table 5). This accuracy problem with the F-Scan's® sensels have been noted by others on curved surfaces (Buis and Convery, 1997; Ferguson-Pell 2000) and could be due to the fact that there is currently no calibration method for the F-Scan® on curved surfaces. Recently, researchers have criticized the accuracy and validity of the manufacturer's recommended method of the calibration (the Baumann compensation) for flat surfaces for which the system was designed (Sumiya *et al.*, 1998; Woodburn and Helliwell, 1996). With some additional research, however, the F-Scan® problems may be correctable through the development of appropriate curved surface calibration methods in combination with allowing longer settle times than 2 minute.

In terms of test-retest reliability both systems were quite variable when test-retest data are considered in Tables 2 and 3. Although statistical analysis cannot be performed given that only two trials were collected per load condition; the mean measured pressures shown in

Table 2 for the XSENSOR®, had less variability from back-to-back tests compared to measured mean pressures collected during test-retest conditions for the F-Scan® (Table 3). These findings suggest that the XSENSOR® might be more reliable than the F-Scan®, although both systems need several trials of data collected to ensure that the standard error of the mean is smaller. In addition, results are more repeatable for longer durations. Observation of Figure 3, which shows a sample of test-retest data for the XSENSOR®, shows a constant state of creep for short duration loading and reloading. In essence, observation shows that, during the retest condition, the plot of the retest load becomes a continuation of the creep from the initial load. Therefore, there is continuous creep during short-duration loading. To correct this, both systems will need further study and perhaps some software compensations for creep.

## 7.0 Conclusions

In conclusion, the Hadcock (2002) model is valid for resolving force vectors from pressure measurement systems, into normal forces on curved surfaces. Using the shoulder model, the XSENSOR® was shown to be more accurate then the F-Scan® when loads were allowed to settle for a minimum of 5 minutes. However, the XSENSOR® is currently not recommended for short 2-minute duration loading measurements on a curved surface, due to degraded accuracy under these conditions. Further, the XSENSOR® was shown to have excellent accuracy compared to the F-Scan® system during hip model testing. It should be noted that F-Scan® was working at the lower end of its scale where inaccuracies may be more prevalent. Results from this study suggest that the XSENSOR® has excellent potential for use on human soldiers, although more testing is required to develop software algorithms to improve repeatability and accuracy during short duration loading applications on curved surfaces.

## 8.0 Next Steps

In this study the XSENSOR® was compared to our current system, F-Scan®, to determine if it performed better on a curved surface. Although the XSENSOR® performed better, more testing is also required to develop software computer algorithms for improved repeatability and accuracy during short duration loading applications on curved surfaces. Further, more testing is also required to deal with the problems of creep. Lastly, once the system is better understood and the software is modified, then testing may progress to testing using models with a variety of contoured shapes. Once the XSENSOR® is modified, testing can eventually begin on human subjects.

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## Appendix A - Raw Data

Raw Statistical Data for Short Duration Accuracy and Repeatability Testing on using the XSENSOR® on the Shoulder Model using Middle 50% of Samples Collected.

**Descriptives**

F2

| | N | Mean | Std. Deviation | Std. Error | 95% Confidence Interval for Mean Lower Bound | 95% Confidence Interval for Mean Upper Bound | Minimum | Maximum |
|---|---|---|---|---|---|---|---|---|
| 1.00 | 57 | 10.6967 | .1289 | 1.707E-02 | 10.6625 | 10.7309 | 10.45 | 10.97 |
| 2.00 | 58 | 10.7635 | 7.774E-02 | 1.021E-02 | 10.7430 | 10.7839 | 10.63 | 10.97 |
| 3.00 | 58 | 14.6039 | .2637 | 3.463E-02 | 14.5345 | 14.6732 | 14.17 | 15.03 |
| 4.00 | 58 | 16.4679 | .1546 | 2.029E-02 | 16.4272 | 16.5085 | 16.09 | 16.81 |
| 5.00 | 58 | 18.1126 | 6.257E-02 | 8.216E-03 | 18.0962 | 18.1291 | 18.01 | 18.23 |
| 6.00 | 58 | 18.3769 | .1028 | 1.350E-02 | 18.3499 | 18.4039 | 18.25 | 18.61 |
| Total | 347 | 14.8488 | 3.1593 | .1696 | 14.5153 | 15.1824 | 10.45 | 18.61 |

Figure A-1: Raw Data

# Appendix B: Test-re-test Results

Test-re-test results with the F-Scan® system on the hip model (as extracted from Hadcock (2002)

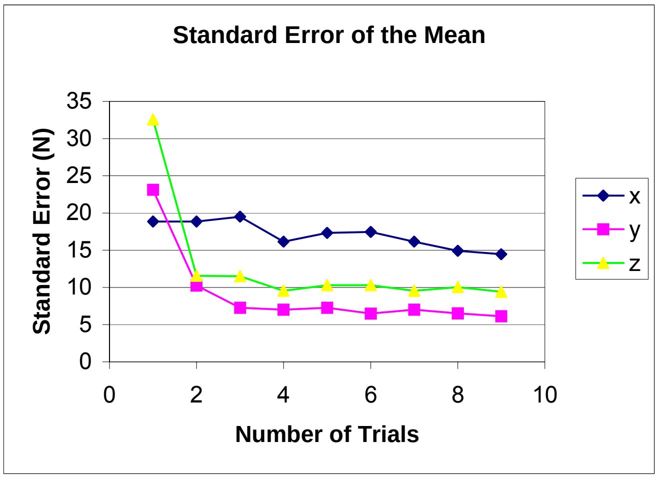



Figure B1. Standard Error of the Mean of summed forces on a waist belt.

Sum of forces in the x, y, and z directions is shown over nine trials using F-Scan® data.

**Appendix C:** Example of Instructions for Use of a Pressure Sensor (XSENSOR®) on the Shoulder and Lower Torso Models.

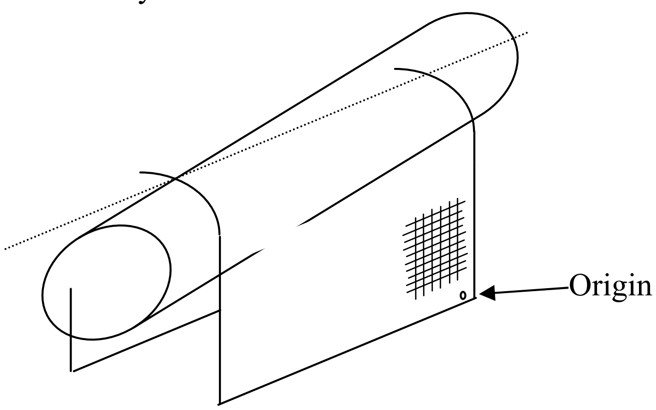
Analysis Spreadsheets

The spreadsheets for data analysis resolve the measured force vectors into directional components in the x, y, and z directions. These values are summed to produce single scalar values representing the force in three dimensions.

Mounting of the Shoulder Sensor

Place the sensor, right side up on the shoulder tube. The origin should be in the position shown below. The middle of the sensor, between rows 18 and 19 should lie along the top of the tube. The sensor should be taped in place along the ends.

If overlapping occurs, the overlap areas must be taken into consideration when the data is analyzed. The overlapping area must be zeroed in the collected data as including it will create redundancy and inaccurate results.




The sensor should be placed, right side up, on the SLT with the top row corresponding with the upper edge of the lumbar or abdominal area. The line separating columns 18 and 19 should be centred in line with the midpoint on the upper edge of the lumbar or abdominal area, as shown below.

Shoulder Data Collection and Analysis

Affix the sensor to the shoulder as in 'Mounting of the Sensor'.

Apply the load to the shoulder.

Determine whether any overlap is occurring. If overlap is present, note which sensels are affected, in order to zero those sensels in data analysis. For example, if rows 30-36 are overlapped by rows 1-6, replace the measured values of data in rows 30-36 with zeroes in the raw data section of the spreadsheet.

Allow the load to settle for a minimum of 2 minutes as it tends to swing with the orientation of the shoulder apparatus.

Record the trial.
Save the file as an XSENSOR file as backup and export the data as a ‘text’ files, average of all points. (File>Export>Average of all points>Add interval (all points)>Save as ASCII)

Unload the shoulder and repeat the procedure a minimum of three times per load to average the results.

Open the ‘XSENSOR Shoulder Template’ file and save it under a new file name – using the testing date in the new name is recommended.

Open the text file for the first trial into EXCEL®. Press ‘finish’ as the default settings are correct.

Copy the values in the 36 columns and rows. Do not copy headers.

Paste special (‘Values’) into the worksheet labelled “Trial 1 - raw’.

If any overlap occurred during testing, change the corresponding values to zeros in the raw data.

The worksheet “Trial 1” outputs the values as X, Y, and Z values and converts them to Newtons. The raw sum, with no curvature effects, is shown for comparison.

SLT (Lower Torso) Data Collection and Analysis

Affix the sensor to the SLT as in ‘Mounting of the Sensor’.

Apply the load to the SLT.

Determine whether any overlap is occurring. If overlap is present, note which sensels are affected, in order to zero those sensels in data analysis. For example, if rows 30-36 are overlapped by rows 1-6, replace the measured values of data in rows 30-36 with zeroes in the raw data section of the spreadsheet.

Record the trial.

Save the file as an XSENSOR® file as backup and export the data as a ‘text’ files, average of all points. (File>Export>Average of all points>Add interval (all points)>Save as ASCII)

Unload the SLT and repeat the procedure a minimum of three times per load to average the results.

Open the ‘XSENSOR® SLT Template’ file and save it under a new file name – using the testing date in the new name is recommended.

Open the text file for the first trial into EXCEL®. Press ‘finish’ as the default settings are correct.

Copy the values in the 36 columns and rows. Do not copy headers.

Paste special (‘Values’) into the worksheet labelled “Raw Data Input - Trial 1”.

If any overlap occurred during testing, change the corresponding values to zeros in the raw data.

The worksheet “Output - Trial 1” outputs the values as X, Y, and Z values and converts them to Newtons. The raw sum, with no curvature effects, is shown for comparison.

**Appendix D:** Sample Spreadsheet used for Data Analyses (XSENSOR® examples for the shoulder)

Sample Raw Data File For 9.8 Kg Load

Sample Raw Data File For 14.4 Kg Load

Sample Raw Data File For 19.0 Kg Load

F-Scan Results 9.802 kg nominal load
Average Pressure on sensor

| | | | | | |
|---|---|---|---|---|---|
| F-Scan Results 9.802 kg | Trial 1 | 10.74 kPa | Trial 2 | 9.98 kPa |
| | Stdev | 0.11 kPa | | 0.11 kPa |

Trial 1 Raw - data in N's

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0.00 | 0 | 0.405 |
| 0 | 0 | 0 | 0.00 | 0 | 0.35 |
| 0 | 0 | 0 | 0.00 | 0 | 0.52 |
| 0 | 0 | 2.86 | 2.57 | 2.79 | 0 |
| 0 | 0 | 2.44 | 2.55 | 0.46 | 0.46 |
| 2.55 | 2.21 | 2.21 | 2.44 | 0.58 | 0.58 |
| 2.44 | 2.09 | 1.86 | 2.44 | 0.46 | 0.46 |
| 2.67 | 2.09 | 0 | 0.00 | 0 | 0 |
| 2.21 | 0 | 2.32 | 2.79 | 0.46 | 0.7 |
| 2.32 | 2.46 | 2.09 | 1.97 | 0.46 | 0.46 |
| 1.74 | 1.97 | 2.09 | 2.40 | 0.46 | 0.35 |
| 2.495 | 2.30 | 0 | 0.00 | 0 | 0 |
| 2.53 | 0 | 2.32 | 2.79 | 0.58 | 0.405 |
| 1.97 | 2.44 | 2.11 | 2.25 | 0.58 | 0.58 |
| 2.21 | 1.88 | 2.21 | 2.09 | 0 | 0 |
| 2.21 | 2.21 | 0 | 0.00 | 0 | 0 |
| 0 | 0 | 0 | 0.00 | 0 | 0 |

**Total appplied Force = 103.895 N**
STDev 1.090055 N
Varience 1.188221 N

F average 	**100.2242 N**

Find # of active sensels

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 1 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 0 | 0 |
| 1 | 1 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 |

Total # of active sensels = 60 sensels
9677.4 mm^2
0.009677 m^2
(Area: 0.25 in^2= 0.25*645.16 mm^2

**Area Avg 0.009677 m^2**

Trial 2 Raw - data in N's

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0.58 |
| 0 | 0 | 0 | 0 | 0 | 0.35 |
| 0 | 0 | 0 | 0 | 0 | 0.58 |
| 0 | 0 | 2.44 | 2.67 | 2.32 | 0 |
| 0 | 0 | 2.32 | 2.21 | 1.74 | 0.5 |
| 0.56 | 2.44 | 2.44 | 2.09 | 1.63 | 0.62 |
| 0.46 | 2.79 | 2.21 | 2.09 | 1.74 | 0.46 |
| 0.66 | 2.61 | 0 | 0 | 0 | 0 |
| 0.35 | 0 | 2.44 | 2.55 | 1.86 | 0.77 |
| 0.58 | 3.02 | 2.21 | 1.97 | 1.86 | 0.46 |
| 0.52 | 1.95 | 2.21 | 2.21 | 1.97 | 0.46 |
| 0.7 | 2.44 | 0 | 0 | 0 | 0 |
| 0.39 | 0 | 2.67 | 2.42 | 1.97 | 0.46 |
| 0.46 | 2.21 | 2.28 | 2.09 | 1.86 | 0.58 |
| 0.35 | 2.44 | 2.23 | 1.97 | 0.81 | 0 |
| 0 | 2.32 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 |

**Total appplied Force 96.55333 N**
STDev 1.03573 **N**
Varience 1.072737 N

Find # of active sensels

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 1 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 |

Total # of active sensels = 60 sensels
9677.4 mm^2
Area = 0.009677 m^2
Area: 0.25 in^2=0.25*645.16 mm^2

F-Scan Results 14.402 kg nominal load
Average Pressure on sensor

| | | | | | |
|---|---|---|---|---|---|
| F-Scan Results 14.40 | Trial 3 | 13.19 kPa | Trial 4 | 12.08 kPa |
| | Stdev | 0.11 kPa | | 0.10 kPa |

Trial 1 Raw - data in N's

| | | | | | |
|---|---|---|---|---|---|
| 0.00 | 0.00 | 0.00 | 1.10 | 3.52 | 0.00 |
| 0.00 | 2.53 | 1.76 | 2.42 | 5.06 | 0.88 |
| 0.66 | 4.18 | 1.98 | 2.42 | 4.40 | 0.88 |
| 3.08 | 4.40 | 1.76 | 2.57 | 4.18 | 0.88 |
| 0.00 | 3.96 | 1.21 | 2.42 | 3.30 | 0.88 |
| 0.66 | 4.07 | 1.28 | 1.54 | 3.52 | 1.10 |
| 0.66 | 4.18 | 1.54 | 2.20 | 4.14 | 0.88 |
| 0.00 | 4.18 | 1.61 | 1.54 | 3.52 | 0.66 |
| 0.00 | 2.42 | 0.88 | 1.54 | 3.08 | 0.88 |
| 0.11 | 2.53 | 1.10 | 1.76 | 3.30 | 0.66 |
| 0.66 | 2.86 | 0.95 | 1.98 | 3.08 | 0.66 |
| 0.00 | 2.64 | 1.10 | 1.98 | 3.30 | 0.88 |
| 0.00 | 3.08 | 1.76 | 1.54 | 3.30 | 0.92 |
| 0.00 | 3.30 | 1.76 | 1.98 | 3.19 | 1.10 |
| 0.00 | 2.86 | 1.98 | 1.76 | 4.18 | 0.66 |
| 0.00 | 0.00 | 0.00 | 0.11 | 2.16 | 0.55 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Total appplied Force** **172.26 N** F averag **169.895 N**
STDev 1.4042 N
Varience 1.9718 N

Find # of active sensels

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 1 | 1 | 0 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 0 | 0 | 0 | 1 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 |

Total # of active sensels = 81 sensels **Area Avg** **0.013468 m^2**
13064 mm^2
0.0131
(Area: 0.25 in^2= 0.25*645.16 mm^2

Trial 2 Raw - data in N's

| | | | | | |
|---|---|---|---|---|---|
| 0.00 | 0.00 | 0.00 | 0.00 | 1.76 | 0.66 |
| 0.00 | 0.88 | 1.94 | 2.20 | 3.74 | 0.88 |
| 0.66 | 4.95 | 1.76 | 2.42 | 3.96 | 0.88 |
| 2.86 | 5.06 | 1.98 | 1.98 | 3.96 | 0.88 |
| 0.73 | 4.40 | 1.32 | 1.98 | 3.56 | 0.66 |
| 0.66 | 4.18 | 1.50 | 1.94 | 3.78 | 0.92 |
| 1.10 | 4.18 | 1.54 | 1.98 | 4.18 | 0.66 |
| 0.88 | 4.18 | 1.32 | 1.54 | 3.74 | 0.66 |
| 0.33 | 2.64 | 1.10 | 1.54 | 2.86 | 0.66 |
| 0.66 | 2.86 | 1.25 | 1.80 | 2.86 | 0.66 |
| 0.66 | 2.64 | 0.81 | 1.54 | 3.26 | 0.66 |
| 0.66 | 3.08 | 1.10 | 1.54 | 2.86 | 0.66 |
| 0.55 | 3.74 | 1.32 | 1.10 | 2.86 | 0.66 |
| 0.00 | 3.52 | 1.10 | 1.43 | 3.08 | 0.88 |
| 0.00 | 3.08 | 1.10 | 1.32 | 3.48 | 0.66 |
| 0.00 | 0.00 | 0.66 | 0.66 | 2.64 | 0.00 |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Total appplied Fc** **167.53 N**
STDev 1.36377 N
Varience 1.85987 N

Find # of active sensels

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 |

Total # of active sensels = 86 sensels
13871 mm^2
Area = 0.0139 m^2
Area: 0.25 in^2=0.25*645.16 mm^2

F-Scan Results 19.037 kg nominal load
Average Pressure on sensor

| | | | | | |
|---|---|---|---|---|---|
| F-Scan Results 19.037 | Trial 5 | 17.73 kPa | | Trial 6 | 19.90 kPa |
| | STDev | 0.25 kPa | | STDev | 0.27 kPa |

Trial 1 Raw - data in N's

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 2.64 | 3.08 | 5.06 | 8.14 |
| 0.66 | 0.66 | 3.08 | 2.42 | 3.08 | 8.14 |
| 3.3 | 0.66 | 3.52 | 2.42 | 2.42 | 7.88 |
| 0 | 0 | 1.54 | 0.953 | 1.98 | 7.30 |
| 0 | 0 | 1.1 | 0.66 | 1.76 | 7.7 |
| 0 | 0 | 0.95 | 0.66 | 2.64 | 7.22 |
| 0 | 0 | 1.1 | 0.66 | 1.32 | 6.38 |
| 0 | 0 | 0.66 | 0 | 0 | 5.54 |
| 0.66 | 0 | 0 | 0 | 0 | 5.94 |
| 0.66 | 0 | 0 | 0 | 0 | 5.06 |
| 0.44 | 0 | 0 | 0 | 0 | 5.43 |
| 0 | 0 | 1.54 | 1.1 | 1.54 | 5.5 |
| 0 | 0 | 1.54 | 1.247 | 1.54 | 5.5 |
| 0 | 0 | 1.76 | 1.54 | 1.83 | 6.16 |
| 0 | 0 | 0.66 | 0.11 | 1.58 | 1.54 |
| 0 | 0 | 0 | 0 | 0 | 0 |

**Total appplied Force** **160.16 N** F averag **169.965 N**
STDev 2.27503 **N**
Varience 5.17578 N

Trial 2 Raw - data in N's

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1.32 | 1.1 |
| 0 | 0 | 3.3 | 2.2 | 2.42 | 7.92 |
| 0.66 | 0.66 | 3.96 | 2.64 | 2.2 | 8.14 |
| 3.08 | 0.44 | 4.18 | 2.86 | 2.49 | 8.59 |
| 0 | 0 | 1.76 | 0.88 | 1.76 | 8.37 |
| 0 | 0 | 1.54 | 1.1 | 1.54 | 8.37 |
| 0 | 0 | 1.98 | 1.54 | 1.98 | 8.14 |
| 0 | 0 | 1.76 | 1.1 | 1.54 | 7.48 |
| 0 | 0 | 0.66 | 0 | 0 | 6.38 |
| 0 | 0 | 0.88 | 0 | 0 | 6.12 |
| 0 | 0 | 0.66 | 0 | 0 | 5.5 |
| 0 | 0 | 0.33 | 0 | 0 | 5.5 |
| 0 | 0 | 2.42 | 1.98 | 1.32 | 6.34 |
| 0 | 0 | 2.42 | 1.98 | 1.54 | 5.94 |
| 0 | 0 | 2.86 | 2.2 | 1.76 | 6.93 |
| 0 | 0 | 1.32 | 0 | 5.72 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 |

**Total appplied Fo** **179.77 N**
2.45912 N
Varience 6.04725 N

Find # of active sensels (Trial 1)

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 0 | 0 | 1 |
| 1 | 0 | 0 | 0 | 0 | 1 |
| 1 | 0 | 0 | 0 | 0 | 1 |
| 1 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 |

Total # of active sensels = 56 sensels **Area Avg** **0.00903 m^2**
9032.24 mm^2
0.00903 m^2
(Area: 0.25 in^2= 0.25*645.16 mm^2

Find # of active sensels (Trial 2)

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 |
| 0 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 |

Total # of active sensels = 56 sensels
9032.24 mm^2
Area = 0.00903 m^2
Area: 0.25 in^2=0.25*645.16 mm^2

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4. AUTHORS (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)

M.A. Fergenbaum; L. Hadcock; J.M. Stevenson; J.T. Bryant; E. Morin; S.A. Reid

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(U) Soldiers experience pressure as a result of their personal load carriage system acting on the shoulder and back. As such, an experimental measurement tools must be able to accurately and repeatability measure pressures on these curved surfaces.

The purpose of this study was to examine pressure measurement systems on curved surfaces resembling the shoulders and the hips. To accomplish this, a method developed by Hadcock (2002) that resolves normal force vectors into vertical and horizontal components was used to test the validity using two different pressure measurement technologies: the XSENSOR® X36 model by XSENSOR® Technology Corporation and the F−Scan (F−socket series) model by Tekscan Incorporated.

The testing jigs used in this study were a cylindrical shape for the shoulder and an elliptical shape for the hips. Under ideal test conditions, results showed that the XSENSOR® had a 2% accuracy error on the shoulder and 4% accuracy on the hip, which is notably better than the 72% accuracy error on the shoulder model and 53% accuracy error for the hip model found for the F−Scan®. The F−Scan® errors were due primarily to working at the low end of the sensor's range and bending the mylar around a 114 mm diameter cylinder that induces a preload on the sensels.



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(U) Load carriage; Dynamic Biomechanical Model; Pressure measurement systems; XSENSOR®; F−Scan; Shoulder Model Testing



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