PRESSURE MEASUREMENT APPLICATIONS FOR HUMANS

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Pressure systems have been used to assess contact pressures acting on human tissues, yet the accuracy of these systems is not clear. Three modern pressure technologies were tested on flat and curved surfaces under static and dynamic conditions: F-scan (Tekscan Inc.), FSA (Vista Medical Ltd.), and Xsensor (Xsensor Technology Corp.). The FSA and Xsensor had similar accuracy and both performed better than the F-scan on flat surfaces, although the Xsensor was more accurate at low pressures. On curved surfaces the Xsensor was more accurate than the F-scan and was less affected by the radius of curvature. For dynamic testing, the Xsensor was more repeatable and accurate than the FSA. Overall, the Xsensor performed superior and the F-scan performance was the most limited.

Key words: Tekscan, Vista Medical, Xsensor

LES APPLICATIONS DES MEASURES DE PRESSION POUR LES HUMAINES

Des systèmes de pression ont été employés pour évaluer des pressions de contact agissant sur les tissus humains, pourtant l'exactitude de ces systèmes n'est pas claire. Trois technologies modernes de pression ont été examinées sur les surfaces plates et incurvées dans des conditions statiques et dynamiques: F-scan (Tekscan Inc.), FSA (Vista Medical ltd.), and Xsensor (Xsensor Technology Corp.). Le FSA et le Xsensor ont eu l'exactitude semblable et exécutents mieux que F-scan sur les surfaces plates, bien que le Xsensor ait été plus précis à la basse pression ait eu moins de fluage. Sur les surfaces incurvées le Xsensor était plus précis que F-scan et moins avez été affecté par le rayon de courbure. Pour l'essai dynamique, le Xsensor était plus fiable et précis que le FSA. De façon générale, le Xsensor a démontré une exécution supérieure, tandis que, F-scan était le système de pression le plus limité.

Les Mots Clés: Tekscan, Vista Medical, Xsensor

INTRODUCTION

Anytime the human body comes in contact with another object, compressive forces are applied to an area of the skin. To better understand how contact pressure affects human comfort and performance, accurate and reliable technology is needed to measure the contact pressures on flat and curved surfaces, under static and dynamic conditions. Studies of pressure sensing technology are inconsistent and most have involved flat surface testing of resistive ink technology such as the F-scan. Performance reports of the F-scan cite accuracy errors as high as 62% (5, 15) and ±19% creep (4). In comparison, studies of the accuracy of capacitance sensors, such as the Pedar (Novel Electronics, Inc.), have reported both no difference between the F-scan and Pedar (14) and better accuracy for the Pedar (9). Further, studies of piezoresistive sensors such as the FSA (Vista Medical, Inc.) have shown pronounced ±19% hysteresis and 4% creep (4), while others have been inconclusive due to methodological weaknesses (10).

Analyzing pressures on curves is more complex, since sensors only measure normal forces. On curves, force vectors must be resolved into x, y and z vectors to validly compare pressures on different contoured surfaces (5, 12). When force vectors were not resolved Polliack et al. (13) showed the F-scan had 11% measurement error on a curve compared to an 8% error on a flat surface. Further, radii between 19-87mm have been shown decreased accuracy for pneumatic sensors (2) and reduce outputs for the F-scan (3).

To improve accuracy, Holewijn (8) developed a model to convert pressures on a shoulder into vertical forces to calculate strap forces for a backpack; however, the shoulder was assumed to be a frictionless cylinder and the model was never validated. More recently, MacNeil (11) developed and validated a 2-strap model which included friction to measure backpack shoulder strap pressures using the F-scan; however, the author noted a need for a calibration method on a curve. Expanding on this work, Hadcock (5) developed a model which included friction to calculate 3-D backpack waist strap forces and she developed an in situ method to calibrate the F-scan using an elliptical human-sized lower torso model. Despite the success of the model, Hadcock noted a 52.6% measurement error using the F-scan and noted the inability of the F-scan to measure shear.

Pressure mapping has also been used for dynamic pressure analysis. Recently, gait research has shown differences between F-scan and force plate data to be as high 37% (6). Confounding factors affecting dynamic studies, include: gait variability between individuals and within individuals from trial-to-trial (12); dynamic pressures applied outside the calibrated range (10, 17); mechanical breakdown of sensors and hot, humid environments

(12); and sensors that detect pressures too soon, too late or completely miss gait events (16).

Given the current literature, the purpose of this study was to evaluate three different modern pressure systems under static and dynamic conditions on flat and curved surfaces.

METHODS

Three pressure systems were tested: a resistive ink technology (F-Scan F-socket model, 9811 pad, version 4.21 software, by Tekscan Incorporated) a capacitance technology (X2 seat model, X36 pad, version 4.1 software, by Xsensor Technology Corporation) and a piezoresistive technology (Seat UT model, version 4.1 software, by Vista Medical Limited). All systems were newly calibrated before testing.

For flat testing, the pressure pad was placed on 3mm thick Bocklite foam over a flat wooden table. All sensor pads were marked with white tape to ensure that the loads were placed on the same sensors and the software was set to sample at 1Hz. Three different protocols were performed: an incremental loading test, a low threshold test, and a creep test. For the incremental loading protocol, each pressure pad was loaded for 2 minutes with loads between 9.392kg - 19.627kg. Each loading was separated by a 1-2 minute interval with no load. The low threshold protocol involved testing each pad at a 1 unit of pressure above the manufacturer's recommended lowest threshold for 20.0 minutes. Consequently, the FSA was tested at 2.2mmHg (0.293kPa), the F-Scan was tested at 1 PSI (6.89kPa) and the Xsensor was tested at 11mmHg (1.47kPa). The creep test protocol involved loading each pad with an 18.627kg mass for 56.8 minutes.

For curved surface testing, a 3mm thick Bocklite foam was glued to a circular pipe (diameter=114mm) and each pressure pad was placed on the pipe (Figure 1). A 4.9 cm wide strap was placed over the sensor pad on a pre-marked area to ensure test consistency and the software was set to collect at 1 Hz. A 9.84 Kg strap-basket-load apparatus was suspended from the pipe and levelled with a bubble level for each trial. Following 5 minutes of settling, data were recorded for 2 minutes. Three trials were collected and equipment was unloaded from the sensor between each trial. Only the F-scan and Xsensor were tested since the sensing areas were clearly marked by the manufacturer; as well, all sensors were tested beforehand to ensure that the load was within each calibration range. The Hadcock (2002) method for resolving strap forces in the x, y, and z planes was adapted to resolve 2-D strap forces in the x and y planes; however, the 2-D model did not incorporate friction or shear.

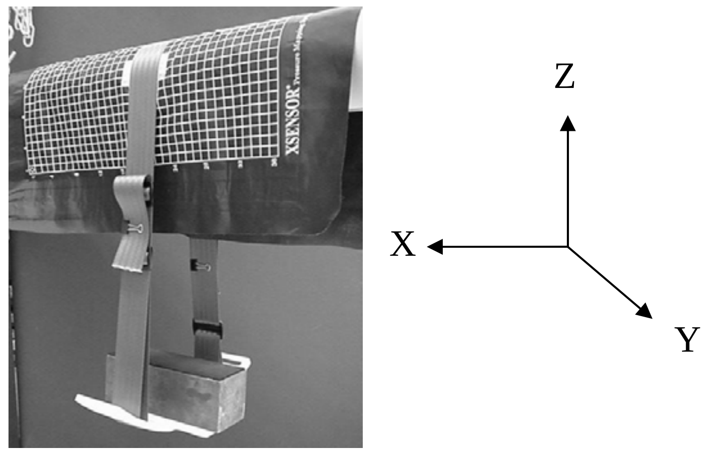

Figure 1 – Set up for curved surface testing.

For dynamic testing, the base of an Instron 5500R dynamic was covered with a 3mm thick Bocklite and the pressure pad was placed over top (Figure 2). Each pressure system was programmed for maximal data collection (12Hz for the FSA and 30Hz for the Xsensor). To apply even loading, the top of the Instron had a universal joint mounted with a circular metal plate (7.4cm in circumference). The Instron was programmed to administer a preload of 20 N at 90N/s for 5 seconds, followed by a trigger to align Instron data with pressure data (a sudden drop in applied force from 20N to 10N at 90 N/s); followed by the cycling program (application of 10 cyclic loads between 10N and 90N). To maintain loading in the calibration range for each pad, the Instron cycling program was programmed to load the sensors at 90N/s and 65N/S for the FSA and Xsensor, respectively, which was calculated based on knowing the maximal applied load and the area of the circular metal attachment from the Instron (max pressure = max force/area).

Figure 2 – Set up of a pressure pad in the Instron 5500R.

To analyze data from all testing, data were normalized by dividing the measured pressure and/or force from the pressure pad by the theoretical predicted pressure and/or force of the load. For incremental and low threshold testing, the middle 50% of the collected samples were used for accuracy analysis. To determine accuracy for the creep protocol the last 25% of the samples collected were analyzed; however, all data collected were analyzed to determine the percent creep. Curved surface data were calculated based by resolving forces in 2-D by Hadcock (5).

RESULTS

All normalized flat test results are summarized in Table 1. Creep as a percentage was found to be 19.54% for the FSA, 17.23% for the F-Scan, and 17.62% for the Xsensor.

Table 1: Normalized flat surface results

Test	FSA	F-Scan	Xsensor
Incremental Test	0.745	2.47	0.751
Low Threshold Test	1.81	2.92	1.03
Creep Test	0.768	2.29	0.778
Average of All Tests	1.11	2.56	0.853

For curved surface testing, the expected force was 96.50N for both systems in the z-direction. For trials 1-3, the F-scan normal force was resolved to 137.29N, 188.29N, and 170.64N in the z-direction. For trials 1-3, the Xsensor normal force was resolved to 95.12N, 95.32N, and 94.34N in the z-direction. The mean force in the z-direction was 165.73N ± 25.90N and 94.93N ± 0.52N for the F-scan and Xsensor, respectively. The normalized value in the z-direction was 1.72 and 0.98 for the F-scan and Xsensor, respectively. The expected force was 0 N for both systems in the x-direction. The mean force of all three trials in the x-direction was 3.73N ± 1.37N for the Xsensor and 0.699N ± 1.04N for the F-scan. The coefficient of variation for the mean force in the z-direction was 0.005 for the Xsensor and 0.16 for the F-scan.
For dynamic testing, the Instron applied an average peak force of 90.48N ± 0.11N to the FSA pad and the Instron coefficient of variation was 0.00122. The FSA measured the average peak force of 32.63N ± 6.8N and the coefficient of variation was 0.208. The Instron applied an average peak force of 90.21N ± 0.041N to the Xsensor and the Instron coefficient of variation was 0.000454. The Xsensor measured the average peak force of 46.32N ± 0.62N and the coefficient of variation was 0.0134. The normalized value for all peak forces was 0.36 and 0.51 for the FSA and Xsensor respectively. When all

eight cyclic loads were compared, the FSA measured a mean force of 10.20N ± 0.52N when the Instron applied a mean force of 50.12N ± 28.24N and the Xsensor measured a mean force of 28.56N ± 1.03N when the Instron applied a mean force of 51.38N ± 27.25N. The coefficient of variance for the mean applied force was 0.051 and 0.036 for the FSA and Xsensor respectively.

DISCUSSION

On flat surfaces, this study showed the FSA and Xsensor had similar accuracy, underestimating pressures approximately 25% when loaded for 2 minutes (incremental loading) and the accuracy was only slightly improved with a longer settle time (creep test). In contrast, the F-scan had greater error than the up to 62% reported by Sih (15). This difference could be due to the method of exporting the data used in this study. In this study, the authors relied on the F-scan system to properly identify the contact area of applied pressures. However, visual examination of the software showed that not all sensors were detecting pressure, even though all sensors were fully covered by the load. Since the F-scan software gives the option to either export only active sensors for analysis or to export all sensors as a group, researchers choosing the latter would find lower pressure averages than those found in this study. Nonetheless, this study was consistent with others have reported that the FSA is more accurate than the F-scan (4), the Xsensor is more accurate than the F-scan (7), and the Xsensor and FSA systems performed with similar accuracy for a variety of pressures (7). In this study, creep for the F-scan (17.23%) and the Xsensor (17.62%) were slightly better than the creep found for FSA and these values are similar to the 12% and 19% reported by others (4, 13). In addition, the 19.54% creep found in this study for the FSA was higher that the 4% creep previously reported (4). Finally, results from this study showed that the Xsensor was superior at light pressure which may be due to the fact that capacitance sensors do not require a charge amplifier unlike piezoresistive sensors (1).

On the curved surface (radius = 57mm) the results of this study showed that the Xsensor was extremely accurate when used with the adapted Hadcock 2002 model and that accuracy of the Xsensor was negligibly affected by the radius of curvature (2% error), in contrast to other studies which reported accuracy problems on curves with radii of 19mm - 87mm (2) and accuracy errors (11%) when used on curved prothestic limbs (13). F-scan data did show reductions in pressure outputs on in the software similar to Buis and Convery (3); however, given that only active sensors were exported for analysis, the final results showed higher pressures than expected.

For dynamic testing, the normalized values for peak pressures were 0.36 and 0.51 showing an underestimation of actual peak dynamic forces by 64% and 49% for the FSA and Xsensor respectively. These values are notably larger than the 37% error shown in past gait studies using the F-scan (6). The larger errors in this study may be due to the more highly controlled, repeatable loading using the Instron (0.1% Instron coefficient of variation). This study was able to eliminate problems involving: gait variability between and within individuals (12); loading beyond the calibration range (10, 17); and hot and humid environments (12).

CONCLUSIONS

The FSA and Xsensor performed better than the F-scan on flat surfaces, although the Xsensor was more accurate at low pressure had less creep than the FSA. Further the Xsensor was superior to the F-scan when vector forces were resolved on a curve and the Xsensor was more accurate than the FSA for dynamic use.

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