Assessment of Geometric and Mechanical Parameters in Wheelchair Seating: A Variability Study

Cathy Maltais, Jean Dansereau, Rachid Aissaoui, and Michèle Lacoste

Abstract—A measurement method has been developed to quantify the posture of able-bodied subjects seated in their wheelchair. Fourteen geometric parameters were measured in order to represent the pelvis, trunk and lower limbs orientations. They were defined by digitizing the three-dimensional (3-D) position of 23 anatomical landmarks using a mechanical articulated arm (Microscribe3D, Immersion Corporation). Mechanical parameters were used to measure the maximum pressure, mean pressure and peak pressure gradient on the seat and the back of the wheelchair using a force sensing array (Vista Medical, Inc.). A third set of parameters combining mechanical and geometric measurements were defined to represent pelvic tilt and ischial pressure orientations. However, different types of errors are associated to the measurement of these geometric and mechanical parameters. The purpose of this study was to evaluate these errors and their impact on the precision of the various parameters on a sample group of five able-bodied subjects. Results showed that variability of most of the geometric parameters is below 2° with the sagittal rotation of the pelvis presenting the highest variability (3.8°) and the thigh angle the lowest one (0.5°). The variability of the mechanical parameters were respectively equal to 4.9% for the mean pressure, 9.3% for the peak pressure gradient and 16.9% for the maximum pressure under ischial tuberosities. It is suggested that the method proposed in this paper could be used as an accurate procedure to characterize the posture of subjects sitting in a wheelchair.

Index Terms—Measurement, parameter, posture, seating, variability, wheelchair.

I. INTRODUCTION

The general purpose of seating is to improve pressure distribution, alignment and comfort [1]. Adequate posture has been defined as a posture where muscle tension is minimized and support forces are equally distributed [2]. Several studies have tried to establish a relationship between posture and pressure distribution on the seat [3]–[6]. Hobson [3] showed a relationship between forward flexion of the trunk segment and pressure value recorded at the body-seat interface. He found that maximum pressures can be reduced by 28 and 9% when the trunk was flexed to 50° for able-bodied and spinal cord injured (SCI) group of subjects, respectively. However, Koo et al. [4] found a reduction of maximum pressure under the ischial tuberosities of about 15.6 and 30% when the trunk was flexed to 45°, for the normal and SCI groups. In terms of posture, Hobson and Tooms [5] observed that the pelvis moved anteriorly by 8 and 15° when the trunk was flexed to 30° using an X-ray technique, while Koo et al. [4] found an anterior pelvic tilt of 13.6 and 5.6° when the trunk was flexed to 45° using external markers for the able-bodied and SCI group, respectively. Although multiple subjects were used in these studies, the repeatability of measurements was not assessed in general, except for one subject in the study of Koo et al. [4] who reported a variability of 1.6° for the A/P pelvic tilt.

When anthropometric, geometric or pressure measurements are collected, several errors can be introduced due to the method and instrumentation used. To evaluate the accuracy of the measurements, reproducibility tests must be done. Variability has been studied for geometric measurement from three-dimensional reconstruction of scoliotic spines and rib cages. It was found that the mean variation of the spinal curvature in the frontal plane (as measured by the Cobb angle) was 0.6° [7]. Evaluation of pelvic position has been performed for automobile seats. Since its exact position was not known, the variability was estimated from standard deviation of changes in length of vectors between various pelvic landmarks. The variability of the distance between left and right anterior superior iliac spine was equal to 18.4 mm [8]. Variability of mechanical measurements such as mean and maximum seat pressure has also been studied. Bader and Hawken [9] found that the variability in maximum pressure under the ischial tuberosities was equal to ±13 mmHg (±1.7 kPa), when the subject remained still seated. However, they showed that repositioning the subject on the cushion produced statistically significant changes in all pressure parameters. Allen et al. [10] investigated the repeatability of subject/bed interface pressure measurements. They found that the overall repeatability of pressure measurement was equal to ±5.8 mmHg (±0.8 kPa). Recently, Swain and Peter [6] reported a considerable variation of ischial pressures ranging from 48 mmHg (6.4 kPa) to 194 mmHg (25.9 kPa) in a group of 27 elderly ambulatory subjects. Although these studies used quantitative measurements in the postural evaluation of wheelchair users, literature is limited on the topic and qualitative measurements are still used in seating research. Furthermore, there is a need for clinical tools and methods to characterize quantitatively the seated posture of a person in wheelchair. The objective of this paper is threefold: 1) to introduce a method to assess the three-dimensional position of the seated subjects based on external anatomical landmarks, 2) to define a set of geometrical and
mechanical parameters as well as the combination of them to characterize the seated posture, and 3) finally, to present results of a variability study of these parameters and anatomical landmarks on a group of able-bodied subjects seated in a wheelchair.

II. METHODS

To study the variability of the geometric and mechanical measurements, a sample group of five able-bodied was constituted (four males and one female). The mean age was 28 years (range from 24 to 33 years). Twenty-three anatomical landmarks were used to define the geometric measurements whereas sixteen wheelchair landmarks were also used to represent the wheelchair orientation in space as well as to locate the position of the seat pressure mat with respect to the wheelchair (Table I). To digitize these landmarks, an articulated mechanical arm (Microscribe3D, Immersion Corporation) was used to track the position and orientation of the stylus in the three-dimensional (3-D) space. The accuracy of the articulated mechanical arm is 0.64 mm (as reported by the manufacturer) and its workspace is a sphere of 1.67 m of diameter. To reach all landmarks, the mechanical arm was placed on each side of the wheelchair. The landmarks on the right side of the human body were collected with respect to the right coordinate system (RCS), whereas the landmarks on the left side were collected with respect to the left coordinate system (LCS) (Fig. 1). Prior to collect anatomical and wheelchair landmarks, the position and the orientation of the RCS was calculated with respect to the LCS. All landmarks were then transformed onto the LCS. Finally, a gravitational coordinate system (GCS) referenced to the wheelchair was defined. The origin of the GCS was fixed on the center of the left rear wheel. The $X$-axis represents the gravitational line; it was obtained by digitizing two landmarks on a metal road aligned with a plumb line. The $Z$-axis is the cross product of the interwheel axis and the $Y$-axis and represents the forward direction of the wheelchair. The $X$-axis is defined as the cross product of $Z$ and $Y$ vectors. Three planes were defined as associated to the GCS: the frontal plane as the $X-Y$ plane, the transverse plane as the $Z-X$ plane and the sagittal plane as the $Y-Z$ plane. Fig. 2 illustrates a graphical representation of a typical posture of a human body seated on a wheelchair obtained with the above specified techniques and defined on the GCS.

To quantify pressure distribution, a pressure mat system (Force Sensing Array, VistaMed, Inc.) was used on the seat of the wheelchair. This system consists of a matrix of 225

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### TABLE I

<table>
<thead>
<tr>
<th>ANATOMICAL LANDMARKS</th>
<th>Identification</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral malleolus (left &amp; right)</td>
<td>1,13</td>
<td>2</td>
</tr>
<tr>
<td>Condyle of femur (left &amp; right)</td>
<td>2,14</td>
<td>2</td>
</tr>
<tr>
<td>Greater trochanter (left &amp; right)</td>
<td>3,15</td>
<td>2</td>
</tr>
<tr>
<td>Anterior superior iliac spine (left &amp; right)</td>
<td>4,16</td>
<td>2</td>
</tr>
<tr>
<td>Iliac crest (left &amp; right)</td>
<td>5,17</td>
<td>2</td>
</tr>
<tr>
<td>Middle trunk (left &amp; right)</td>
<td>6-9, 18-21</td>
<td>8</td>
</tr>
<tr>
<td>Acromion (left &amp; right)</td>
<td>10,22</td>
<td>2</td>
</tr>
<tr>
<td>Cervical vertebrae (C7)</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>Xyphoid process</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Suprasternal notch</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>23</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>WHEELCHAIR LANDMARKS</th>
<th>Identification</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear wheel center (left &amp; right)</td>
<td>1,2</td>
<td>2</td>
</tr>
<tr>
<td>Metal road markers</td>
<td>3,4</td>
<td>2</td>
</tr>
<tr>
<td>Seat matrix markers</td>
<td>5,16</td>
<td>12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

* see figure 2.
§ The four points were marked in the middle part of the rib cage when the subject was lying supine on a bed with legs in 90° flexion.
† see figure 1.
‡ Twelve markers were located equidistantly to represent seat mat.
sensors. Each sensor has an active area of 1.4 cm by 1.9 cm. Pressure measurement has been studied in the past, and it was found that pressure transducers were consistent with a standard deviation of ±15 mmHg (2 kPa) [15]. The accuracy of interface pressure measurement was found to be within the interval of 12 and 15% for the Talley pressure system [14]. Ferguson-Pell and Cardi [13] have evaluated the FSA system and found that the precision was equal to ±10 mmHg (±1.3 kPa), and the FSA was rated well in clinical measurement. Furthermore, this study was conducted with model dated by June 1991. The actual FSA system used in this study has an accuracy of ±5 mmHg (±0.7 kPa). Before each experiment, the pressure mat was calibrated according to the procedure proposed by the manufacturer.

III. DEFINITIONS OF PARAMETERS

To evaluate the position of the user in his/her wheelchair, three types of parameters were defined in order to represent body segment orientations and joint angles of the pelvis, trunk and lower limbs. Fourteen geometric parameters were defined based on the 3-D position of the 23 anatomical landmarks (Table I). Three mechanical parameters were defined based on pressure measurements. Finally, five parameters based on both 3-D positions and pressure measurements were also defined. For some of these parameters, more than one definition are suggested in order to determine which ones provide the least variability and/or the best representation of segment orientations. The following sections describe the three categories of parameters.

1) Geometric Parameters: Pelvic parameters were defined according to Koo and coll. [4], where slight modifications were done related to the accessibility of anatomical landmarks.

a) Pelvic obliquity: PO1: Defined as angle between the transverse plane and the line joining the left and right ASIS, projected on the frontal plane. PO2: Defined as the angle between the transverse plane and the line joining the left and right iliac crests, projected on the frontal plane.

b) Pelvic transverse rotation: PTR1: Defined as the angle between the frontal plane and the line joining the left and right ASIS, projected on the transverse plane. PTR2: Defined as the angle between the frontal and the line joining the left and right iliac crests, projected on the transverse plane.

c) Pelvic tilt: PT1: Defined as the angle between the transverse plane and the best fit plane formed by the left and right ASIS and the left and right trochanters. PT2: Defined as the angle between the transverse plane and the best fit plane formed by the left and right ASIS and the left and right iliac crests.

d) Knee angles: KAL: Defined as the angle between two lines joining the left malleolus, left condyle of femur and left trochanter projected on the sagittal plane. KAR: Defined as the angles between two lines joining the right malleolus, right condyle of femur and right trochanter projected on the sagittal plane.

e) Hip angles: HAL: Defined as the angle between two lines joining the left condyle of femur, left trochanter, and the left iliac crest projected on the sagittal plane. HAR: Defined as the angle between two lines joining the right malleolus, right condyle of femur and right trochanter projected on the sagittal plane.

f) Thigh angles: TAL: Defined as the angle between the transverse plane and the line joining the left condyle of femur and the left trochanter. TAR: Defined as the angle between the transverse plane and the line joining the right condyle of femur and the right trochanter.

g) Trunk lateral tilt: TLT: Defined as the angle between the sagittal plane and the best fit plane formed by the inferior and superior extremity of the sternum and C7.

h) Trunk transverse rotation: TTR: Defined as the angle between the frontal plane and the best fit plane (obtained by singular value decomposition [11]) calculated from the eight points marked on the middle of each lateral side of the trunk.

2) Mechanical Parameters: Mechanical parameters were defined to characterize the pressure distribution between the subject and the wheelchair cushion. Maximum pressures, mean pressures and pressure gradients were defined from pressure distribution measurements on the wheelchair’s seat. Based on the assumption that it is possible to isolate two regions related to the ischial tuberosities, two sides were defined on the pressure mat system (left and right). The separation was delimited as the median line of sensors between the thighs.

- Maximum Pressure: Defined as the maximum value of the pressure distribution evaluated on each region (MaxL, MaxR).
- Mean Pressure: Defined as the mean pressure of the pressure distribution evaluated on each region (MeanL, MeanR).
- Pressure Gradient: Defined as the partial derivative in the two directions (x,y), Gradients were evaluated for all sensors and maximum value of each right and left
region was kept for analysis (Peak_L, Peak_R):

\[ P = f(x, y) = \text{pressure} \]

\[ \text{Gradient}(x, y) = \sqrt{\frac{\partial P^2}{\partial x} + \frac{\partial P^2}{\partial y}} \]

3) Parameters Combining Mechanical and Geometric Measurements: A third type of parameter combining mechanical and geometric measurements was used to represent pelvic tilt and ischial pressure orientations. To determine which measures in the sagittal plane provide the best representation for pelvic tilt and its physiologic posture, several approaches were defined. So, in addition to geometric parameters obtained with the 3-D digitizer, three other pelvic tilt parameters combining geometric and mechanical measurements were defined (PT3, PT4, PT5). These three parameters were based on the location of the ischial tuberosity determined by the identification of the pressure sensor situated just under the ischial tuberosity. This was done by palpation; the clinician placed his hands between the subject and the cushion and pressed on the sensor corresponding to the ischial tuberosities. Geometric position of the center of the sensors was used to estimate ischial tuberosity position. Definition of these three pelvic parameters are the followings.

a) Pelvic tilt: PT3: Defined as the angle between the transverse plane and the best fit plane formed with the trochanters and the position of the ischial tuberosities evaluated on the pressure matrix. PT4: Defined as the angle between the transverse plane and the best fit plane formed with the iliac crest and the position of the ischial tuberosities evaluated on the pressure matrix. PT5: Defined as the angle between the transverse plane and the best fit plane formed with the iliac crest and the position of the ischial tuberosities evaluated on the pressure matrix.

b) Ischial pressure orientations: Defined on the pressure representation as the angle formed by the projected line joining the maximum pressure values in the frontal plane (IPOF: ischial pressure orientation in the frontal plane) and in the transverse plane (IPOT: ischial pressure orientation in the transverse plane). Fig. 3 illustrates these two last parameters.

IV. TESTING PROCEDURES

All subjects were provided with a manual wheelchair (Prima, Orthofab Inc.) and a 2-in polyurethane foam cushion. The wheelchair was fixed on the support platform. No modification was done on the wheelchair. For each experiment, the subject was asked to sit in a comfortable position, recommendations were made to the subjects to stay in the same position during the experimentation. The objective of the first four tests was to establish the variability of geometric measurements, while the objective of the 5th test was to evaluate the variability of parameters associated with mechanical measurements.

Test 1: The objective of the first test was to measure the variability of the seated position.

Step 1) The landmarks presented in Table I were marked on each subject with a pen. To make the location process more consistent for each test, the same clinician was asked to locate these landmarks.

Step 2) The subject was asked to sit in the wheelchair and the landmarks were digitized in 3-D with the mechanical arm.

Step 3) The subject was asked to stand up and walk for two minutes. This test was repeated three times from Step 2).

Test 2: The purpose of the second test was to evaluate the variation in the identification of the landmarks. The subject
remained in the wheelchair for the entire experiment. The clinician digitized the landmarks four times with the mechanical arm (without doing pen marks on the subjects). Variability of anatomical landmarks position was evaluated for this specific test and only three subjects were tested.

**Test 3:** The third test combined the two previous tests and was performed to evaluate the variability of the seated posture combined with the variability of the identification of the landmarks.

Step 1) The subject was asked to sit in the wheelchair and the landmarks were marked with a pen by the clinician.

Step 2) The marks were digitized and then erased. The subject stood up and the test was repeated two times from Step 1). Variability of geometric parameters was evaluated.

**Test 4:** This test was done to assess the repeatability of digitizing process. The subject was asked to sit in the wheelchair for the duration of the experiment and the landmarks were marked by the clinician. Each mark was digitized three times with respect to the sequence presented in Table I (all landmarks of the left sides were digitized first).

**Test 5:** This last test was performed to evaluate variability of all parameters associated with pressure measurements.

Step 1) Landmarks on the iliac crests, trochanters and ASIS were marked by the clinician on the subject in the seating position.

Step 2) The pressure matrix was placed on the wheelchair and position of the 12 landmarks on the matrix was recorded with the mechanical arm.

Step 3) The subject was asked to sit in the wheelchair for 20 s while pressure distribution was recorded at a frequency of 8 Hz. Average pressure value of the 20 s acquisition was used for analysis.

Step 4) Position of ischial tuberosities were evaluated by the clinician by palpating and pressing the corresponding sensors on the matrix.

Step 5) Position of the iliac crest, trochanter, and ASIS was digitized with the mechanical arm.

Step 6) The subject stood up, waited two minutes and then sat down again in the wheelchair. The procedure was repeated three times from Step 2). Variability of maximum pressure, mean pressure, pressure gradient, ischial pressure orientations and pelvic tilt (PT3, PT4, and PT5) was evaluated.

**V. STATISTICAL ANALYSIS**

In order to verify if the variability for one parameter is roughly the same for all subjects, Levene’s test of homoscedasticity was performed [12]. Since the exact position of the different segments is not known, variability was defined as the standard deviation of the centered data [7]. Consequently, measurements were centered around zero by subtracting the average corresponding to each subject. Variability of each parameter was obtained by calculating the standard deviation of the centered data as a group of 20 measurements (four trials × five subjects). For test 2, only 15 measures were used (three trials × five subjects).

For the mechanical parameters, a Kruskal–Wallis one way nonparametric ANOVA test was performed for each subject to analyze the variability of pressure measurement. For each subject, the 30 frames of pressure distribution for each trial were used for analysis. Mechanical parameters (maximum pressures, mean pressures and peak pressures for right and left sides) were computed for each of these 30 frames and comparison between each trial was performed.

**VI. RESULTS AND DISCUSSION**

Homoscedasticity was confirmed ($p < 0.05$) for the geometric parameters of test 1 and test 3. This result of the Levene test implies that variation around the mean had a similar random deviation and that the centered data is consequently an adequate representation of each parameter [7]. Homoscedasticity was not confirmed for the results of test 4. Parameter values evaluated for the fourth test present small variability ($\approx 1^\circ$). The relatively small difference of deviation around the mean between each subject explained the results of Levene’s test. It implies that, for this test, variation around the mean does not had a similar random deviation between each subject.

Fig. 4 presents the variability of geometric measurements for tests 1, 3, and 4. Results showed that variability of most of the geometric parameters is below $2^\circ$ and that the third test presents the highest variability (this test could be associated to a combination of the different factors evaluated in test 1 and test 3). The lowest error was observed for the fourth
TABLE III

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean (M) mmHg (kPa)</th>
<th>Standard deviation (SD) mmHg (kPa)</th>
<th>SD/M %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal pressure (right side)</td>
<td>115.9 (15.4)</td>
<td>19.7 (2.6)</td>
<td>16.9</td>
</tr>
<tr>
<td>Maximal pressure (left side)</td>
<td>117.9 (15.7)</td>
<td>11.2 (1.5)</td>
<td>9.5</td>
</tr>
<tr>
<td>Mean pressure (right side)</td>
<td>46.7 (6.2)</td>
<td>2.6 (0.3)</td>
<td>5.6</td>
</tr>
<tr>
<td>Mean pressure (left side)</td>
<td>53.3 (7.1)</td>
<td>2.6 (0.3)</td>
<td>4.9</td>
</tr>
<tr>
<td>Pressure gradient (right side)</td>
<td>18.2 (2.4)</td>
<td>1.7 (0.2)</td>
<td>9.3</td>
</tr>
<tr>
<td>Pressure gradient (left side)</td>
<td>19.9 (2.7)</td>
<td>2.9 (0.4)</td>
<td>14.6</td>
</tr>
</tbody>
</table>

† Units are in mmHg/cm (kPa/cm)

test. Best results were obtained for parameters associated with the thigh (TAL and TAR) and knee angles (KAL and KAR). Pelvic tilt (PT2) and hip flexion (HAL) present the highest variability. In fact, the common landmarks used in computation of these parameters are the iliac crests. These landmarks are the ones which are the most difficult to be accurately and repeatably identified since they are associated to flat bone without a greater prominence and surrounded by many soft tissues. Landmarks used in the computation of PT1 (trochanter and ASIS) are more repeatable, so the obtained variability is lower than the one used in the computation of PT2. Koo et al. [4] obtained better results of variability for the pelvic tilt measurement (1.6°). Their tests, however, were performed with only one subject using other landmarks such as the coccyx (in the present study, access to the coccyx was obstructed by the back of the wheelchair). Results of test 2 presented on Table II confirm the previous results and show the trochanter, iliac crest and xiphoid process as being less accurate landmarks. Results revealed that pelvic parameters evaluated using ASIS could provide a more precise indication of the pelvic orientation in both transverse and frontal plane since the iliac crest showed more variability than ASIS. This implies that parameters PTR2 and PO2, which are based on the iliac crest, respectively presented higher variability than PTR1 and PO1, which used ASIS landmarks. These results confirmed those obtained by Brodeur et al. [8], where it was reported that the ASIS was the most reliable external landmark for the pelvic region.

Homoscedasticity was confirmed \((p<0.05)\) for all parameters involving pressure measurements (results of the fifth test). Typical values of pressure measurement are 100 mmHg (13.3 kPa), 45 mmHg (6 kPa) and 17 mmHg/cm (2.3 kPa/cm) for maximum pressure, mean pressure and pressure gradient respectively. Results of variability of pressure parameters (Table III) showed that lowest variability is obtained with the mean pressure measurement 2.6 mmHg (0.3 kPa, 4.9%) and the pressure gradient 1.7 mmHg/cm (0.2 kPa/cm, 9.3%). The maximum pressure parameter showed a variability less than 20 mmHg (2.7 kPa, 16.9%). Results of variability were similar for the two regions (left and right); only maximum pressure showed a difference between left and right sides. These variations could be due to the accuracy of the pressure reading system, the movement of the subject during experiment or the modification of the initial posture. Results of the Kruskal–Wallis test demonstrated that in all 30 cases (five subjects × six parameters) statistical difference between mechanical parameters was observed when the subject was reseated. These results confirmed those obtained by Bader and Hawken [9] and implied that one of the factor causing the variability of the parameters is the subject reseating; these variabilities are included in the values computed in this study.

The ischial pressure orientation parameters were defined in order to relate pelvic position to pressure measurements. Ischial pressure orientation in a frontal plane presents high variability (Table IV). Relatively small distance between ischial tuberosities (≈9 cm) and variability of maximal pressure, as shown previously [around 20 mmHg (2.7 kPa)], can explain this result. The last parameter evaluated for this study was the pelvic tilt combining geometric and mechanical measurements. Results showed that parameter PT3 presents the highest variability (Table IV). This parameter is defined by two landmarks relatively close to each other and which are difficult to be identified (greater trochanters and ischial tuberosities). An error on the position of these landmarks would have a high influence on the calculation of this angle. Variability of the pelvic tilt parameters combining geometric and mechanical measurements (PT3, PT4, and PT5) is largely due to the difficulty in accurately defining the ischial tuberosities positions. During the experimentation, the position of the 12 landmarks on the pressure matrix was recorded without any subject sitting in the wheelchair; cushion deformations were therefore neglected in the computation. It was also observed that ischial tuberosities were hardly palpable when the subject was seated with posterior pelvic tilt. Errors could have been introduced by the fact that the position estimated is related to tissues surrounding the ischial tuberosities. Finally, the sliding displacement of the pressure matrix during the experiment may also have contributed to the resulting variability. On the other hand, variability obtained for pelvic parameters PT4 and PT5 is comparable with the one obtained with geometric parameters.
PT1 and PT2. However, if the position of ischial tuberosities could be identified with greater accuracy, parameter PT5 could be considered as a good approximation of the real vertical orientation of the pelvis, which could be used to characterize its neutral position. For the present study, PT1 (defined with ASIS and greater trochanter) seems to be a better approach showing less variability even if it does not give a absolute value of the real anatomical orientation of the pelvic.

Methods proposed in this paper have some limitations. First, difficulty to define geometric parameters is related to the fact that not many external landmarks are accessible when the user is sitting in a wheelchair. The different seating aids obstruct the access to pertinent landmarks such as posterior superior iliac spine, coccyx and spinous process on the spine. Moreover, the length of the articulated arm (0.84 m) limited access to all landmarks (for one position of the mechanical arm). In this study, two positions of the arm (located on both sides of the wheelchair) were required, involving experimentation time of about one hour. If more landmarks were required, other positions of the mechanical arm would be necessary and time of the experiment would increase. In order to reduce experimentation time, other measurement devices might be considered such as video-based motion analysis systems. In this case, the 3-D data would be recorded simultaneously using skin surface markers. In that sense, one of the advantage of the mechanical articulated arm (Microscribe3D, Immersion Corporation) used in the present study was to reach more accurately the real bony anatomical landmarks by compressing the soft tissues, allowing to digitize points as close as possible to the anatomical internal structure.

VII. CONCLUSION

Preliminary results confirmed that the method developed in this study is a noninvasive and sufficiently reproducible procedure for the geometric and mechanical evaluation of the seated posture. Results indicated that variability of most of the geometric parameters is below 2° where pelvic sagittal tilt showed the highest variability (3.8°) and the thigh angle the lowest one (0.5°). Mechanical parameters showed variability of 5.2 and 12% for mean pressure measurement and pressure gradient respectively. The maximum pressure showed a variability less than 13.2%. The pelvic tilt parameter combining mechanical and geometric measurements showed a variability of 4° while the orientation of the ischial pressure in the transverse plane presented the highest variability. This study also suggested that the most accurate pelvic tilt measurement is based on landmarks associated with the greater trochanter and the ASIS (PT1).

Finally, this study introduced a new method and a measurement protocol for the quantitative evaluation of seated wheelchair posture. This evaluation tool, as described in this paper, will allow better characterization and understanding of problems related to the seated posture, which will allow, as a result, to formulate recommendations for the design of more appropriate seating aids oriented toward the needs of the wheelchair users.

Cathy Maltais received the Bachelor degree in mechanical engineering from École Polytechnique de Montréal, P.Q., Canada, in 1996 and the Master degree in biomedical engineering also from École Polytechnique de Montréal, in the field of rehabilitation engineering. Her main interest of research is related to seating aids and wheelchair mobility.

Jean Dansereau was born Montréal, P.Q., Canada, in 1958. He received the B.Eng. and M.Sc. degrees in mechanical engineering from École Polytechnique de Montréal, P.Q., Canada, in 1981 and 1983, respectively, and the Ph.D. degree in mechanical engineering (biomechanics) from the University of Vermont, Burlington, in 1987.

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Michèle Lacoste received the Bachelor degree in occupational therapy from the Université de Montréal, P.Q., Canada, in 1982.

From 1983 to 1996, she worked at the Rehabilitation Institute of Montreal, the Centre hospitalier St.-Michel and in the industry (Promed, Inc.), where she developed an expertise in the field of seating and mobility aids with the adult and elderly population. In 1996, she joined the team of the NSERC Industrial Research Chair on wheelchair seating aids as an Occupational Therapist and Research Associate, where she is responsible for the clinical aspects of the projects and the collaboration with the other clinical institutions.