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Motion Capture System Used for Joint Angle Measurements as an Undergraduate Project

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Abstract:

This paper presents an analysis of the Leap Motion as an occupational therapy tool. The Leap Motion's speed, ease of use, accuracy and price make it a competitive alternative to the goniometer, a commonly used tool for angle measurement. The Leap Motion, a hand gesture tracking system was analyzed with respect to its angle measuring capabilities. Existing software, BREKEL Pro Hands® was used in conjunction with the Leap Motion® to generate an Excel® worksheet of hand data. These data were analyzed utilizing MATLAB® to calculate joint angles. The joint angle measurements were then compared with corresponding angles measured with a goniometer.

Background:

Physical therapy (PT) affects millions of people every year who wish to regain the functional use of a part of their body. PT and occupational therapy (OT) can be costly, and a patient with or without insurance can end up paying out of pocket for therapy sessions. The costs can exceed one hundred dollars a session [1]. This can create a significant financial burden for patients and society. Patients, insurance companies and health care providers all have a stake in tracking therapy progress and patient compliance with OT and PT.

In particular, functional hand motion and grip are important for independent living and quality of life. Often a sufferer's main goal is to get back to doing what they could accomplish before the surgery, accident, or disease process. A common situation is a stiff, frozen or clawed hand which can be the result of a stroke [2]. The patient attends OT to exercise in the context of everyday activities to restore their neuromuscular function. The therapist will first want to do an initial evaluation of the patients' remaining range of motion (ROM). A tool commonly used in hand therapy is the goniometer. Figure 1 is a picture of a goniometer. The two vectors or lines creating the measured angle are outlined. The goniometer is used to measure 14 joint angles in total, three angles, one for each of the joints of the fingers for a total of twelve, and two for the thumb. These are measured twice, once in extension with the hand fully extended and once again with the hand in a closed fist. This results in a total of 28 measurements for one hand. This is then repeated with the second hand, for a total of 56measurements. Due to the large number of angles measured, this can take up to 30 minutes. The goniometer is used as a benchmark of progress with a therapist measuring ROM at the start of therapy to evaluate the deficit and then later times in the healing process to see how the patient has improved. The less time a clinician spends with a goniometer, the more time they can spend working with their patient. The more efficiently a clinician spends their time the less money a patient spends on OT overall.

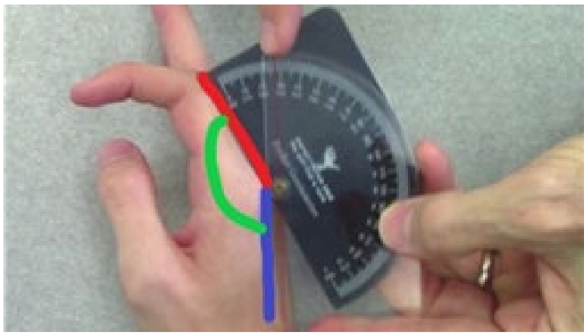

Figure 1

Figure 2

To provide an engineering design solution to improve this situation, we turned to the Leap Motion controller. Figure 2 is a picture of the Leap Motion developed by Leap Motion, Inc. This device is a relatively inexpensive sensor, retailing for approximately eighty dollars (U.S.). It has two cameras and three infrared LEDs to track hand movements [3]. It then uses stereophotogrammetry, a common marker-less motion capture method. Stereophotogrammetry is the estimation of the coordinates of an object based upon images from two or more angles [4]. Leap Motion’s particular method is proprietary. The Leap Motion only recognizes and tracks the hands and forearm, from the tip of the finger to the elbow of the user and the interaction frame or range is five inches to two feet above the sensor. Additionally, the Leap Motion uses an internal tracking model to predict the hand’s position if it cannot be seen by the sensor. However, this tracking system is not entirely accurate as it relies on an algorithm rather than real-time collected hand data. Therefore, its ability to account for a range of hand sizes is limited. The goal of this research is to measure the joint angles of a hand using this sensor in a way that would be fast, easy-to-implement and to understand for the OT or PT clinician.

There are several commercially available sensors for motion tracking, most of which originated in the entertainment industry. We decided to use a Leap Motion rather than other sensors or data gloves for many reasons. Data gloves are prohibitively expensive. They also can be hard to put on a hand with limited ROM [5]. Therefore, they provide no improvement over the current methodology utilizing the goniometer. The XBOX Kinect® [6] uses a similar technology to the

Leap Motion. However, this device captures full body movement for gesture and motion control. The Leap Motion's specialization is for hands and is therefore ideally suited for this project in ways that the Kinect® [7] is not. The internal skeletal model of a left and right hand allows the Leap Motion to make predictions as to the location of all joints of the hand even if they are occluded from the full view of the Leap Motion's cameras. For example, depending upon the rotation at the elbow or wrist, some fingers may obscure others from the cameras. The built-in model and data structures allowed for rapid algorithm development, as did the use of Brekel Pro Hands®.

There has been some significant earlier research about using the Leap Motion for hand therapy. This includes the creation of rehabilitation games, the measurement of the accuracy of the interaction space of the Leap Motion, and the measurement of joint angles with the Leap Motion [8-10]. Leap Motion constantly releases updates to its software to improve hand tracking so new research must be conducted to see if it has become a better tool. Our focus is on the consistency, precision, or repeatability of the measurements in different hand positions.

Methods:

To get hand angles of our test subject, we used Brekel Pro Hands® [11]. Figure 3 is a picture of the user interface of Brekel Pro Hands®. Brekel Pro Hands® is downloadable commercial software primarily for animation industry application development developed by Jasper Brekelmans. It imports raw data from Leap Motion into an Excel Sheet, using Leap Motion's C++ API and takes data every 10^{th} of a second. The user has the ability to adjust a number of data collection parameters, including the smoothing of the data acquisition, which reduces the noise in the image capture. The Brekel software takes data for 133 variables. These variables consist of x, y, z coordinates for every joint for both the left and right hand as well as the positions of the wrist, palm, and elbow. The data for our study were the Euler angles of each joint and the x, y, z coordinates of each joint. Euler angles are the angles of rotation of each joint around the respective local orthogonal Cartesian coordinate frame (figure 4 shows an orthogonal Cartesian coordinate system, xyz, and the associated direct Euler angles a,b,c).

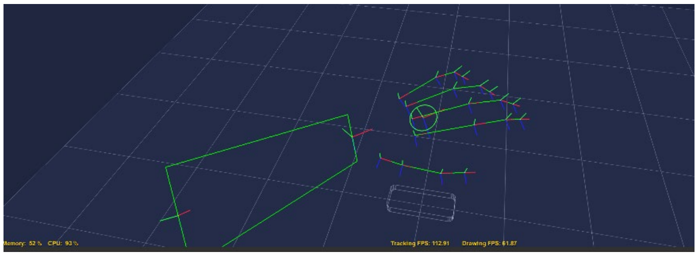

Figure 3

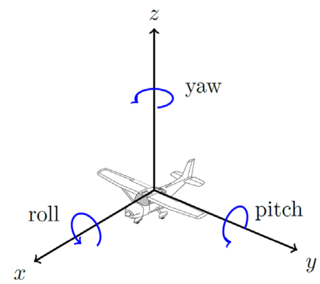

Figure 4

The Leap Motion assigns coordinates to each important section of the hand. Similar to how hands in the real-world function, it bases coordinates of the joints on each other. That is, there is a local coordinate frame at each point relative to the parent point or joint. So, the tip of the finger is based off of the second knuckle which is based off the first knuckle which is based on the base of the finger . This is repeated for each finger. In addition to a translation in space dictated by both the length of the fingers and the relative positions of the joints, the joint angles, one must also take into account the fact that each local reference frame can have a rotation relative to the parent frame. Thus, there is a succession of translations and rotations to form the total transformation of coordinates from one frame to another. The palm, elbow, base of finger, and forearm are all global coordinates. That is, the data is not presented as coordinates relative to each other, but rather as global coordinates relative to the origin of the Leap Motion itself. The Brekel Excel sheet contains a column for each recorded variable and each row represents a moment in time so that the positions are effectively tracked with time. We then exported this Excel sheet into MATLAB®. MATLAB® is a popular programming language developed by Mathworks [12].

Our goal was to remove these reference frames and get everything into global coordinates. Instead of getting coordinates relative to each other, we wanted coordinates relative to the Leap Motion itself. To accomplish this, we used MATLAB®'s function ***eul2rotm*** [13]. This transformed Euler angles into rotation matrices. Rotation matrices are used to transform local coordinates into global coordinates. To transform the tip of the finger there were many steps. We first had to get rotation matrices for each joint of the finger. Then we had to multiply the rotation matrices by each other. The order moves from rotation matrix of the tip to rotation matrix of the second knuckle to rotation matrix of the first knuckle to rotation matrix of the base. This is repeated with the second knuckle and first knuckle. Then we multiplied our rotation matrices by the corresponding x y z coordinates. The next step was to create a vector using the x y z coordinates. Then we took the angle between the two vectors.

This method turned out to be inaccurate, perhaps because of the propagation of errors along the chain of matrix transformations, so we looked at the problem in a new way. The Euler angles provided by Brekel Pro Hands® measure the rotation of the hand. The x y z coordinates can be measured globally as opposed to locally, but adjustment of some software settings. This means they are in relation to the Leap Motion rather than in relation to each other. The Euler angles are also measured globally which means the rotation of each finger was calculated independent of the next joint. To get the angle of each finger joint, we used the rotation of the finger joint in the y direction. This represents the finger's bend along the joint. However, this angle measured the change in angle from one joint to another. The angle that we want is the overall angle. For example, if an open hand has an Euler angle of 0, the angle the goniometer would measure is 180. Therefore, to get the corrected angle we subtracted the Euler angle from 180.

Our goal in this phase of testing our product was precision over accuracy. Precision refers to getting the same results every time no matter the hand position. Whereas, accuracy consists of getting the same result as the goniometer, considered the benchmark or true value, every time. We chose to prioritize precision over accuracy because the primary clinical interest is to see a change with time of ROM and to see it improve. For example, when trying to extend one's fingers, a patient should get angles closer and closer to 180^{o} over time. When they curl or clench their fingers, the angles should get closer and closer to 90^{o}. If the Leap Motion gets the same angle no matter the position of the hand, then it preform well in a clinical setting.

Development of a Handrest:

Figure 5 shows the CAD drawing for a prototype of an armrest to hold patients' hand in the correct position for measurement. After a clinic visit, a modification of this rest is anticipated based on the typical hand-rest used by the OT clinician as shown in Figure 6.

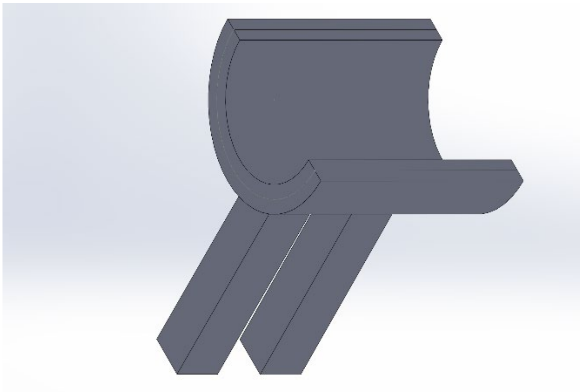

Figure 5

Figure 6

Testing Protocol:

We measured the hand in three different positions: an extended flat hand, a closed hand (fist), and a flat hand with palms turned inwards. The hand open and closed positions were chosen because these are positions that a therapist will use in a clinical setting to asses finger ROM. The third position was chosen because it forces the Leap Motion to rely on its internal tracking model. In this position, the sensor may not be able to detect joints that are obscured by the fingers nearer the detector. Each hand position was measured 8 inches above the Leap Motion in its optimal operating conditions. Each position was measured 10 times. This was repeated with three volunteers.

Results:

In the data we collected for an open hand each joint angle of our volunteers should be 180 because the hand was flat. However, the Leap Motion measured a range of angles from 153 to 180 degrees. The median angle of every data point measured is 174 degrees. We took the mean or average of each joint and plotted it on the graphs below. We also calculated the standard deviation for each finger joint.

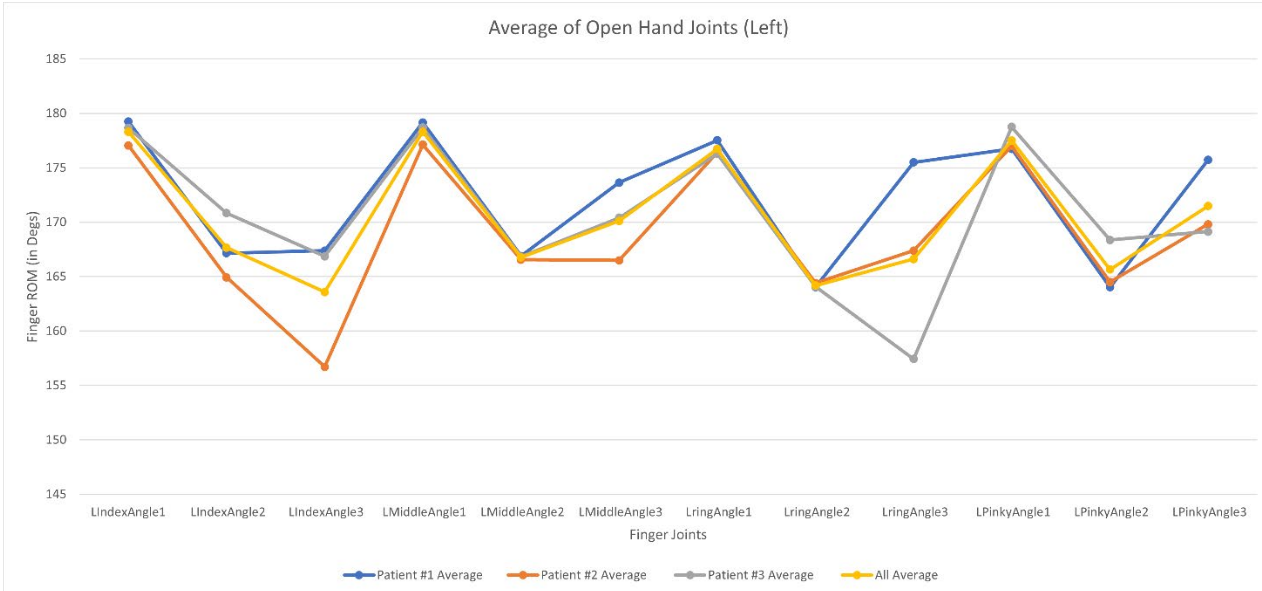

Figure 7

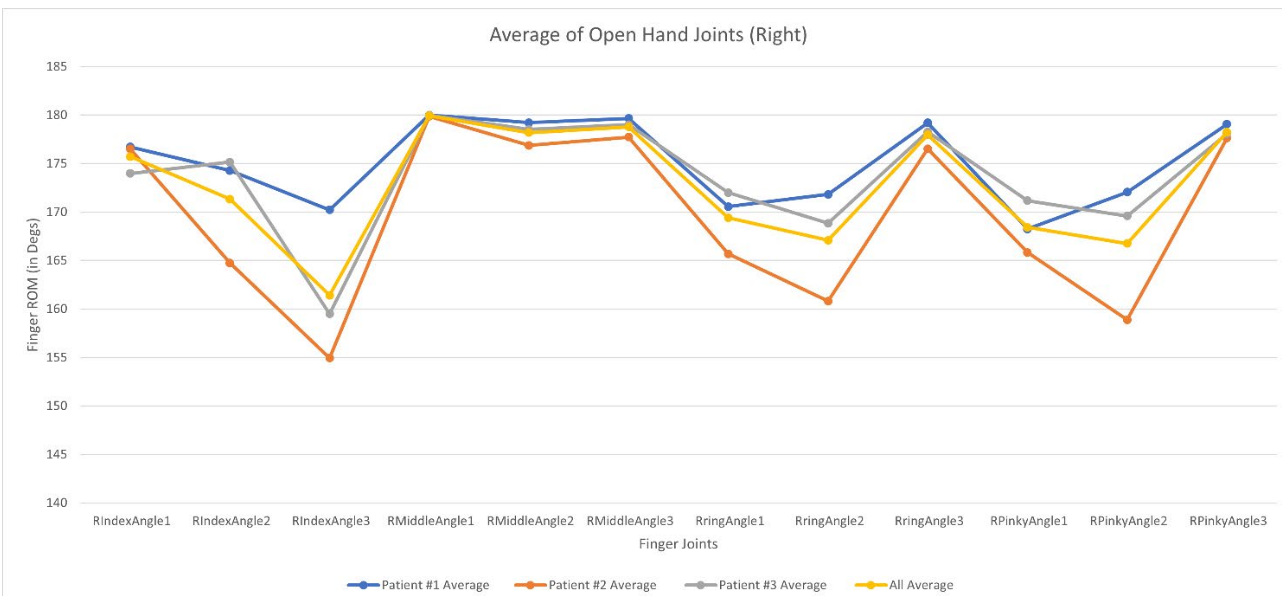

Figure 8

Column1	LIndexAngle1	LIndexAngle2	LIndexAngle3	LMiddleAngle1	LMiddleAngle2	LMiddleAngle3	LringAngle1	LringAngle2	LringAngle3	LPinkyAngle1	LPinkyAngle2	LPinkyAngle3
Patient #1 STDEV	0.39	1.64	2.44	0.43	0.86	1.38	0.43	0.89	1.17	0.32	0.90	1.63
Patient #2 STDEV	1.03	1.74	7.51	0.60	0.82	4.39	0.19	0.94	4.26	0.38	0.66	4.93
Patient #3 STDEV	1.10	2.86	2.66	0.85	2.34	3.83	2.72	7.94	18.31	0.74	1.82	5.19
All STDEV	1.31	3.33	6.86	1.08	1.51	4.55	1.67	4.60	13.11	1.03	2.31	5.25

RIndexAngle1	RIndexAngle2	RIndexAngle3	RMiddleAngle1	RMiddleAngle2	RMiddleAngle3	RringAngle1	RringAngle2	RringAngle3	RPinkyAngle1	RPinkyAngle2	RPinkyAngle3
0.40	0.98	1.51	0.00	0.34	0.22	0.87	1.33	0.41	1.33	1.57	0.50
1.37	5.75	7.12	0.06	0.96	0.77	3.37	5.96	1.00	1.86	5.80	0.60
1.96	4.82	8.59	0.10	1.26	0.61	3.34	5.55	1.01	4.15	5.13	1.12
1.87	6.39	8.97	0.09	1.35	0.98	3.86	6.58	1.39	3.48	7.27	0.98

Figure 9

The data we collected for the fist position cannot be analyzed in the same way as the open hand as the angles of a fist change from joint to joint. This means there will be a greater range of angles overall and the spread cannot be accurately measured. The graphs below show a plot of the average of each joint of the hand. We also calculated the standard deviation of each joint.

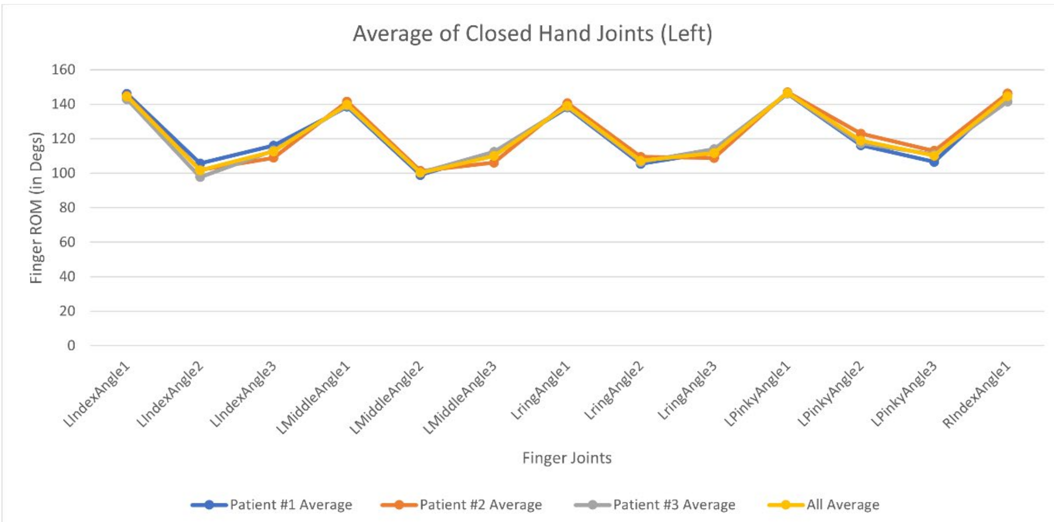

Figure 10

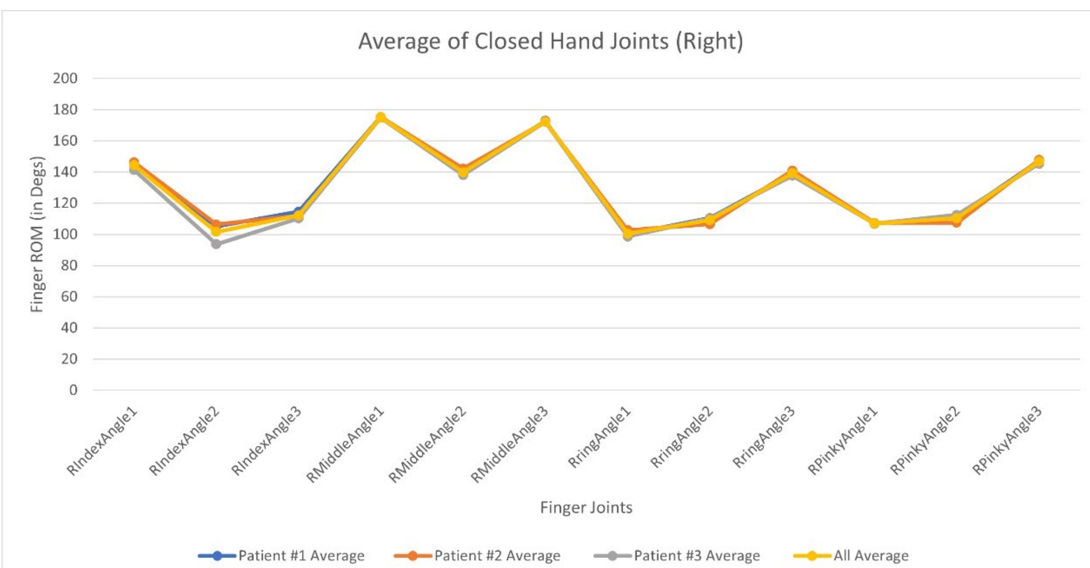

Figure 11

Column1	LIndexAngle1	LIndexAngle2	LIndexAngle3	LMiddleAngle1	LMiddleAngle2	LMiddleAngle3	LringAngle1	LringAngle2	LringAngle3	LPinkyAngle1	LPinkyAngle2	LPinkyAngle3
Patient #1 STDEV	2.19	5.89	2.43	0.43	0.14	0.46	0.36	0.12	0.61	0.37	0.53	0.55
Patient #2 STDEV	1.03	1.91	1.50	0.84	0.84	1.33	0.78	0.70	1.27	0.74	0.81	2.11
Patient #3 STDEV	0.46	1.77	1.09	0.35	0.79	1.29	0.32	0.38	0.95	0.27	0.18	1.61
All STDEV	1.89	4.86	3.42	1.41	1.19	3.04	1.23	1.80	2.35	0.62	3.11	3.03

RIndexAngle1	RIndexAngle2	RIndexAngle3	RMiddleAngle1	RMiddleAngle2	RMiddleAngle3	RringAngle1	RringAngle2	RringAngle3	RPinkyAngle1	RPinkyAngle2	RPinkyAngle3
0.78	2.28	1.04	0.18	0.15	0.28	0.20	0.62	0.20	0.38	0.61	0.22
1.35	2.58	1.01	0.32	0.91	0.45	1.36	1.99	0.84	1.13	1.41	0.45
0.12	0.33	0.80	0.20	0.29	0.32	0.40	0.85	0.34	0.53	0.61	0.25
2.44	6.08	1.93	0.31	1.79	0.43	1.90	2.21	1.50	0.79	2.39	1.10

Figure 12

The data for the hand position of hands flat with palms inwards is displayed below. Each finger angle should be180 degrees as each hand is flat. The rotation of the palms should not affect the measurement. The spread of joint angles is from 160 to 180 degrees. The median angle of all data points is 174 degrees. We also calculated the standard deviation of each angle. Those results are shown in Figure 15.

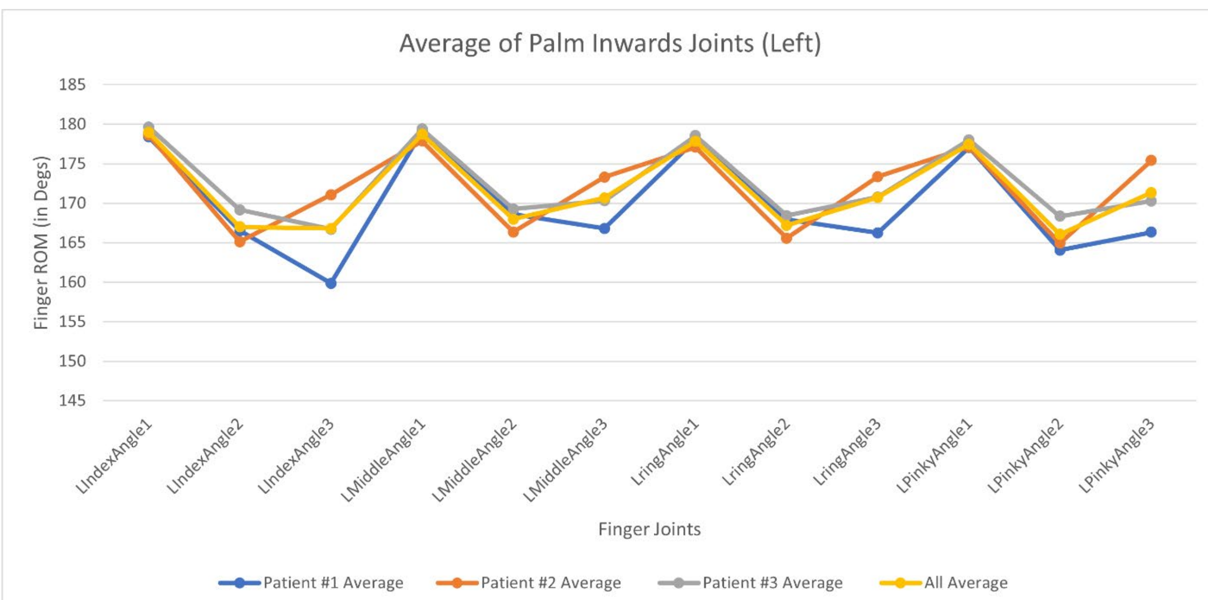

Figure 13

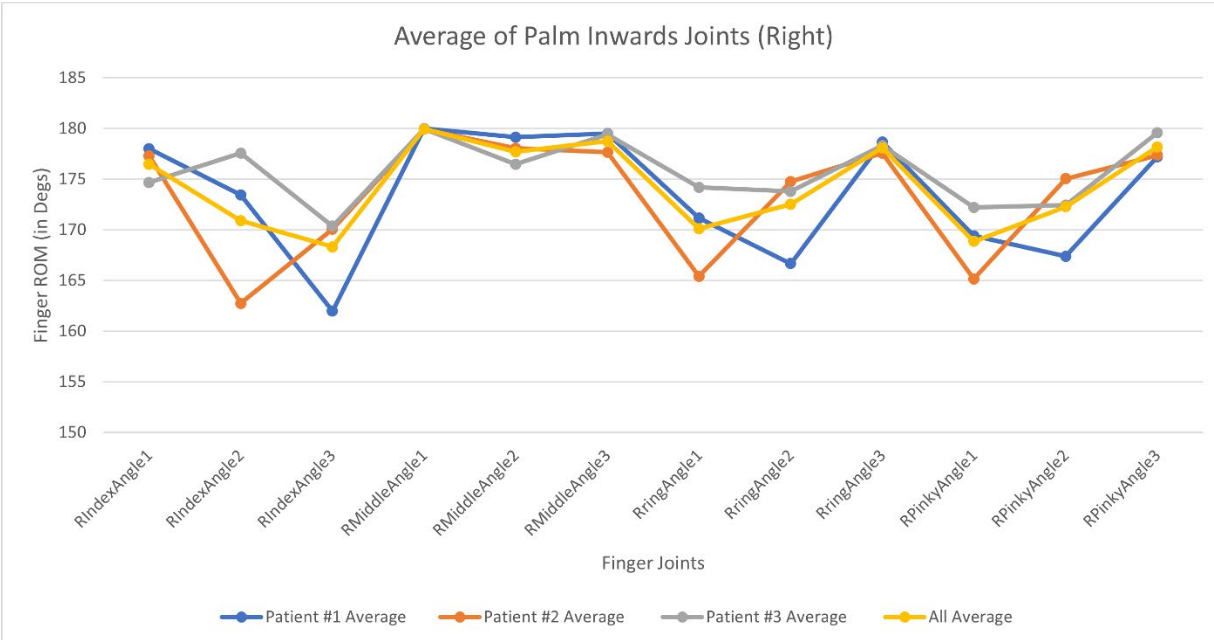

Figure 14

Column1	LIndexAngle1	LIndexAngle2	LIndexAngle3	LMiddleAngle1	LMiddleAngle2	LMiddleAngle3	LringAngle1	LringAngle2	LringAngle3	LPinkyAngle1	LPinkyAngle2	LPinkyAngle3	R
Patient #1 STDEV	1.13	2.51	1.02	0.88	1.01	2.33	0.69	0.65	2.09	0.32	0.74	2.33	
Patient #2 STDEV	0.77	0.99	2.63	0.86	0.83	1.95	1.01	1.12	1.97	0.35	0.96	1.45	
Patient #3 STDEV	0.22	0.52	1.94	0.25	0.34	1.54	0.26	0.51	1.71	0.26	0.57	1.26	
All STDEV	0.89	2.27	4.75	0.97	1.52	3.12	0.96	1.56	3.31	0.54	2.00	3.93	

LPinkyAngle1	LPinkyAngle2	LPinkyAngle3	RIndexAngle1	RIndexAngle2	RIndexAngle3	RMiddleAngle1	RMiddleAngle2	RMiddleAngle3	RringAngle1	RringAngle2	RringAngle3	RPinkyAngle1	RPinkyAngle2	RPinkyAngle3
0.32	0.74	2.33	1.40	3.27	1.52	0.01	0.61	0.36	1.19	1.85	0.61	0.79	0.95	0.16
0.35	0.96	1.45	0.86	2.17	2.24	0.03	0.62	0.20	1.54	2.54	0.51	1.31	2.34	0.45
0.26	0.57	1.26	0.49	1.13	0.65	0.01	0.18	0.16	0.55	0.75	0.31	0.93	0.99	0.25
0.54	2.00	3.93	1.70	7.05	3.87	0.04	1.18	0.93	4.09	3.78	0.66	3.33	3.39	1.17

Figure 15

Discussion: Based upon the results of this experiment we have discovered that the Leap Motion is reasonably precise. The standard deviation of the hand angles we measured vary widely depending on which joint is measured. This could be due to variations in the Leap Motion's tracking and imaging system and the details of how it is utilized. However the standard deviation of the palms turned inward was relatively small which indicates the Leap Motion's internal tracking model is precise and that Leap Motion may be a viable solution to the original problem of reducing the time it takes to measure hand joint angles and flexibility. The testing we completed took much less time than the 30 minutes that the goniometer requires. We believe that the deviation in angles is small enough to be used in a clinical setting, especially if the hand is supported. This will allow the clinician to track changes if the patient cannot be treated in person. All participants in this study were healthy individuals therefore in further research we would like to use patients in a clinical setting to test the Leap Motion's precision. Given that opportunity, standard statistical tests to confirm repeatability and validity against measurements done in the current standard of care would be performed and analyzed. This work was primarily a pedagogical project that achieved several outcomes. Not all the positive outcomes were ones that might have been named prior to the project. Namely it helped to develop a partnership between the university and a clinical hospital setting. It is hoped that the partnership for this and other projects may be continued. Combining the resources available at each institution made such a project possible. Either institution on its own did not have the resources necessary to achieve the outcomes. For the student author it provided that invaluable experience of a hands-on learning project. Most students consistently appreciate and request such opportunities, even as there may be many barriers to providing enough such experiences to all students who may desire them. In this experience, what was especially noteworthy was both the 'hacking' and use of an everyday consumer product. Repurposing the Leap Motion was a significant challenge. 'Opening the hood' of any such product requires significant patience as well as online research with DIY and user communities. Posting questions to various interested groups was invaluable and contacting the developer of the Brekel Pro Hands® interface was very helpful and welcoming to the project. Experiencing the benefits of such user community outreach and communication is an important pedagogical outcome. Often students, especially in traditional four-year degree programs are acculturated to the idea that one must know everything already or that it is cheating to ask or search online and that the only way to learn is to read a textbook. This DIY community provides an important point of leverage that makes such research experiences fruitful, practical, and efficient.

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