ORIGINAL ARTICLE

A Pilot Study on the Functional Outcome using Markerless Motion Analysis Tool and Surface EMG of Nerve Transfers for Upper Trunk Brachial Plexus Injuries

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ABSTRACT

Introduction. Brachial plexus injuries (BPI) have devastating functional effects. Clinical outcomes of BPI reconstruction have been documented in literature; however, these do not use EMG and quantitative kinematic studies.

Objective. This study aims to use a markerless motion analysis tool (KINECT) and surface EMG to assess the functional outcomes of adult patients with traumatic upper trunk BPI who have undergone nerve transfers for the shoulder and elbow in comparison to the normal contralateral limb.

Methods. This is an exploratory study which evaluated three participants with BPI after nerve reconstruction. KINECT was used to evaluate the kinematics (range of motion, velocity, and acceleration) and the surface EMG for muscle electrical signals (root mean square, peak EMG signal, and peak activation time) of the extremities. The means of each parameter were computed and compared using t-test or Mann-Whitney U test.

Results. Participant C, with the best clinical recovery, showed mostly higher KINECT and EMG values for the BPI extremity. There was a significant difference between the KINECT data of Participants A and B, with lower mean values for the BPI extremity. Most of the EMG results showed lower signals for the BPI extremity, with statistical significance.

Conclusion. The KINECT and surface EMG provide simple, cost-effective, quick, and objective assessment tools. These can be used for monitoring and as basis for formulating individualized interventions. A specific algorithm should be developed for the KINECT sensors to address errors in data collection. A fine needle EMG may be more useful in evaluating the muscles involved in shoulder external rotation.

Keywords: brachial plexus injury, upper trunk, kinematics, markerless motion analysis, KINECT, surface EMG

INTRODUCTION

Brachial plexus injuries (BPI) have devastating functional effects on patients, as it involves motor and sensory impairment of varying degrees of the upper extremity. The incidence of BPI is estimated to be 0.64–3.9/100,000/year, with 1.2% in multiply injured patients.[1] Majority of the cases are due to motor vehicular accidents, and the numbers have

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increased over the past years as there is a growing use for these vehicles as a means of transportation.[2]

Treatment options for BPI vary and are individualized depending on the type of injury, time of injury, mechanism of injury, function affected, and concomitant injuries of surrounding tissue.[2-4] Approximately 45% of patients with BPI have an upper trunk injury[5], commonly presenting as lack of shoulder and elbow functions (C5/C6), with weakness to long extensors to wrist and fingers, and to elbow extensors (C7).[6,7] For an upper trunk BPI, Oberlin procedure for elbow flexion and nerve transfers for shoulder abduction were more successful approaches than nerve grafting or combined techniques.[7]

Outcomes of BPI reconstruction have been documented in literature; however, these do not have EMG and quantitative kinematic studies which offer increased sensitivity to detect changes in motion and accuracy and precision of functional assessment.[5-12] These are important in evaluating the upper extremity to identify specific impairments, to plan an appropriate intervention, and to monitor progress for rehabilitation.

EMG and kinematic studies have been widely used for gait and lower extremity analysis. The complexity and non-repetitive nature of the functions of the upper extremity have been difficult to capture by these studies. Surface electromyography is a noninvasive technique that is a quick, valid and reliable indicator for evaluating muscle function in both healthy and pathological populations.[13-18] The validity of a marker-based system for kinematic studies has been studied and established.[19-24] A markerless system addresses the same objectives while offering advantages of patient comfort, less tedious set up, less marker placement errors, cheaper cost, and not necessitating a laboratory to function.[25-31] KINECT, developed by Microsoft, tracks motion in 3D by combining 2D image information from a color camera and a depth sensing infrared camera, using a machine learning algorithm.[25,29,30] It has been used as a markerless motion analysis tool to study kinematics.[25-33] It has demonstrated high accuracy and validity for upper extremity in functional activities of normal and participants with pathology when compared to marker-based motion analysis programs.[25-31]

This study aims to use KINECT and surface EMG to compare the functional outcome of adult patients with traumatic upper trunk BPI who have undergone nerve transfers for the shoulder and elbow with the normal contralateral limb. Currently, there is no literature available on the utilization of these measurements for functional outcome nerve reconstructed upper extremities in brachial plexus injuries. This may help us gain some insights on which muscles are most useful in performing certain ranges of motion (ROM) after reconstructive procedures. This will enable clinicians to identify other key muscles that may need reinnervation or reconstruction in order to improve certain motions of the upper extremity. These in turn may aid in formulating an individualized rehabilitation plan and provide a monitoring tool for patient recovery.

MATERIALS AND METHODS

Participants

Three participants were included in the study. There were 13 participants initially planned for the study, however, due to the prolonged duration of the COVID-19 pandemic and its surges with corresponding restrictions, there were delays in proceeding with the sessions which required face-to-face interactions with the participants.

The following were the inclusion criteria for the participants: (1) all adult patients (18 years old and above) diagnosed with upper and extended upper type brachial plexus injuries treated with nerve transfers for the reconstruction of shoulder and elbow function from January 1, 2003 to December 31, 2018, (2) patients from the database of the UP-PGH Department of Orthopedics Section of Reconstructive Microsurgery, (3) a minimum of 12 months follow-up, (4) unilateral brachial plexus injury, and (5) for both upper extremities, regarding associated injuries, fractures are fixed with acceptable reduction parameters, joints are supple, and no shoulder or elbow joint fusion performed. The participants with the following conditions were excluded from the study: (1) a diagnosis of obstetric brachial plexus injury, (2) bilateral injuries, (3) combination of nerve transfers with other procedures for shoulder and elbow function (eg. Tendon-muscle transfer, nerve grafting), (4) a contralateral upper extremity with existing pathology that can affect muscle strength or ROM, and (5) a post-operative with recovery of less than M3 (Medical Research Council scale) on muscle motor testing for shoulder flexion, abduction and external rotation and elbow flexion.

The study was done at The Department of Orthopedics, University of the Philippines – Philippine General Hospital which houses the Motion Analysis Program / Gait Lab. An informed consent, approved by the Review Ethics Board of the University of the Philippines Manila, was signed by the participant before starting the session. The following anthropometric measurements were taken: height, weight, arm length (the distance between the acromial anterior angle and the lateral epicondyle), forearm length (the distance between lateral epicondyle and the radial styloid), and hand length (the distance between the wrist at the level of the radial styloid and the distal tip of the middle finger).

The Disabilities of Arm, Shoulder, and Hand (DASH) outcomes questionnaire was completed by each participant.

Participant Tasks

There were 4 predetermined tasks analyzed: (1) shoulder flexion (FF) - shoulder forward flexion in sagittal plane and extension back to resting position, (2) shoulder abduction (ABD) - shoulder abduction in frontal plane and adduction back to resting position, (3) shoulder external rotation (ER) from resting position of arms on the side, forearm neutral, elbows flexed to 90 degrees (or to degree capable by the affected limb), shoulder external rotation, and internal rotation back to resting position, and (4) elbow flexion (EF) from resting position of arms on the side, forearm neutral, elbow flexion and elbow extension back to resting position.

Every task was done 8 times for KINECT and then 8 times for the EMG. The participant repeated each task 4 times for every trial (a total of 2 trials), with a period of at least 2 minutes rest in between each trial. The participants accomplished the tasks in their own comfortable speed. The session lasted for 2 hours, wherein the participant performed each task for a total of 16 times per extremity.

Experimental Setup

Goniometer

A standard goniometer was used to measure the ROM (in degrees) of the normal limb and the affected contralateral limb along its central axis for each task. The starting position, as described previously was designated as 0 degree, and the measured angle at end range was the recorded ROM of the participant.

Kinematics

The KINECT V2 system with a sampling frequency of 30 frames per second was set up, placed on a tripod at 2 meters above the floor, 1.5 meters from where the participant stood, tilted 45 degrees to the face of the participant, and separated 80 degrees apart.[30, 31] The sensors were connected to 2 desktop computers and were labeled as LEFT camera and RIGHT camera (Figure 1).

Every trial is completed by the program analysis of a static pose and then the dynamic movement or task of interest (Figure 2). A static position was held by the participant for 5 seconds, allowing the KINECT system to establish the participant local segment coordinates including the torso and upper arms. Then, the participant performed the tasks with both extremities simultaneously. A thick green line in segments seen on the screen indicates successful detection of coordinates. Errors in signals occur when there the thick green line is lost during dynamic motion of the participant causing measurement errors (Figure 3). Data were collected after every trial. The data filename was labeled as "participantID_KINECT_task(FF/ABD/ER/EF)_trial#" (participantA KINECT FF trial1). Each trial produced data for all joint ROM, velocity and acceleration. The data of the corresponding task, matching the filename, were analyzed.

The upper limb kinematics model developed by MATLAB software for the KINECT V2 system was originally designed for another project but was modified for this study by partner engineers from Marquette University.[25-27] It used the three Euler angles for right shoulder motion: flexion (+) / extension (-), adduction (+) / abduction (-), and internal (+) / external (-) rotation. For the left shoulder joint angles, the motion data was mirrored to the right counterpart. The elbow flexion (+) / extension (-) was calculated by the position data from ShoulderRight / ShoulderLeft, ElbowRight / ElbowLeft, and WristRight / WristLeft using trigonometric function. Once the evaluation was complete, the system stored the 3D location of each detected point throughout the duration of testing. MATLAB program was used for data storage and processing. The 3D information was then converted to 2D simplified joint motion analysis using body segments of arm, forearm, and wrist for the study and the detected changes in its position. Detected body segment location data from the KINECT were processed through a validated upper body model in OpenSim musculoskeletal simulation software, as part of the MATLAB-automated process. This modeling approach optimizes segment position, which reduces error by smoothing the KINECT data, and computes triaxial kinematics (joint position for ROM in degrees, velocity in deg/s, and acceleration in deg/s^2). Data with their corresponding labels were exported to Microsoft Excel.

Figure 1. Positioning of the test subject and the 2 KINECT sensors. The 2 KINECT sensors are 1.5 m away from the subject, separated 80 degrees apart, elevated 2 m high and tilted 45 degrees towards the subject.

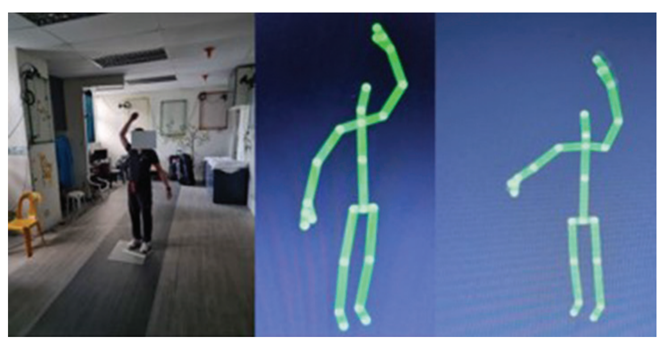

Figure 2. Static position of the test subject and the coordinates registered by the 2 KINECT (LEFT camera and RIGHT camera) sensors as seen on the desktop computers. The thick green lines indicate that the sensors are successfully registering the coordinates.

Electromyography

EMG surface sensors were applied – anterior deltoid (Ch 1), middle deltoid (Ch 2), posterior deltoid (Ch3), biceps brachii (Ch 4), brachioradialis (Ch 5), and triceps long head (Ch 6) (Figure 4). The electrodes were placed on each muscle following Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) recommendations.[34]

Electrical activity produced by the anterior deltoid, posterior deltoid, middle deltoid, biceps brachii, brachioradialis, and triceps long head for both upper extremities was recorded using 6 of the 8-channel set of Delsys Trigno® Wireless EMG sensors at 2000 Hz sampling rate (Figure 5).

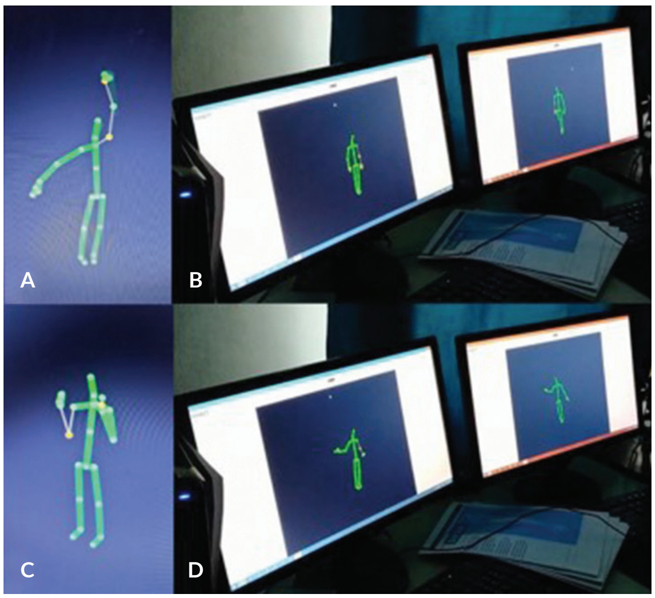

Figure 3. Causes of measurement errors by the KINECT system illustrated by the segments with no thick green line as described by Yeung et al.[51] **(A-B)** Self occlusion by the subject's body. **(C)** Bone length variation as the subject performs the task. **(D)** Artificial vibration as the segment nears even a static segment.

Figure 4. Surface EMG sensors applied on the test subject. Anterior deltoid **(Ch 1)**, middle deltoid **(Ch 2)**, posterior deltoid **(Ch3)**, biceps brachii **(Ch 4)**, brachioradialis **(Ch 5)**, and triceps long head **(Ch 6)**.

Each participant performed the tasks with the normal extremity first with a period of EMG recorded rest for 3 secs done to get the signals for the baseline relaxed state muscle. All tasks were completed without removing the sensors from the extremity. Data were collected after every trial with the filename labeled as "participantID_EMG_extremity (normal/BPI)_task(FF/ABD/ER/EF)_trial#" (participantA EMG normal FF trial1). The procedure was repeated for the contralateral limb with brachial plexus injury.

Each trial produced data for all 6 channels. Only the following muscles were analyzed per task: shoulder flexion (FF) – Channel 1 (anterior deltoid), Channel 3 (posterior deltoid), shoulder abduction (ABD) – Channel 2 (middle deltoid), shoulder external rotation (ER) – Channel 3 (posterior deltoid), Channel 1 (anterior deltoid), and elbow flexion (EF) – Channel 4 (biceps), Channel 5 (brachioradialis), and Channel 6 (triceps long head).

Data Processing

Custom-written MATLAB scripts were written utilizing the Signal Processing Toolbox™ for KINECT and EMG post-processing.

KINECT post-processing

Angular waveforms for the ROM (Figure 6), velocity (Figure 7), and acceleration (Figure 8) were graphed using MATLAB. The maximum and minimum values were identified and the ROM was computed as the difference of the

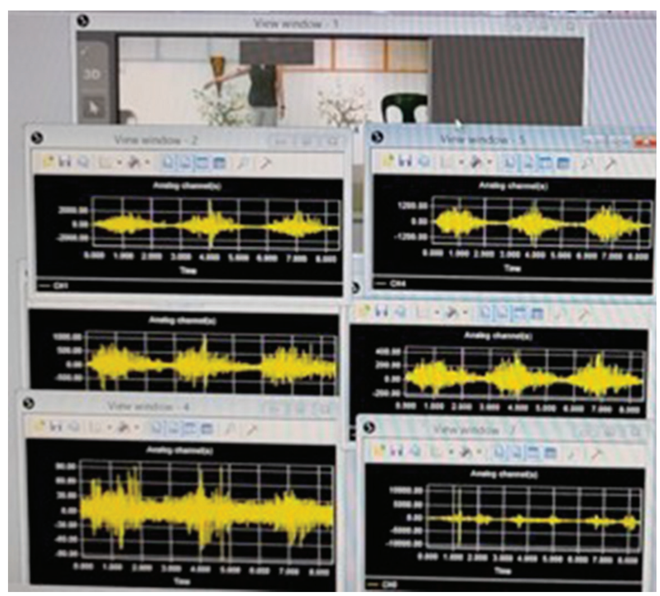

Figure 5. Raw digital signals recorded by the 6 channels of the surface EMG on a test subject, with a video reference synced with the system. This tracks the signals recorded at the specific movement done by the subject. The y axis shows the raw data in millivolts, while the x axis shows the time elapsed.

two values. The positive and negative values for velocity and acceleration were direction dependent, positive corresponding to flexion, abduction and external rotation, and the negative values corresponding to extension, adduction, and internal rotation. The highest positive values were recorded for velocity and acceleration as peak velocity and peak acceleration, respectively.

For every task, every repetition, and each trial, the following were recorded for each extremity: ROM (deg), peak velocity (deg/s), and acceleration (deg/s^2).

EMG post-processing

Determination of onset and offset times

All raw digital EMG signals were bandpass filtered (10 Hz – 450 Hz) using a digital 4th order Butterworth filter and rectified. The rectified EMG signals were low-pass filtered using a digital 2nd order Butterworth filter with cut-off frequency at 20Hz. The standard deviation (SD) and mean (μ) over non-overlapping consecutive 300ms window were recorded for the relaxed state of each muscle per participant per condition and task across all trials.[35] The mean value of the window with the smallest SD and mean for each trial were obtained. This information was used to calculate the threshold voltage for each muscle per subject ($T_{subj,m}$) using the formula:

$$T_{subj,m} = \mu_{subj,m} + hSD_{subj,m}$$

Where h=3 as set by the operator.[36] The onset times (offset) were recorded when the subject's processed EMG signal for the muscle m is greater than (less than) the threshold voltage for at least 25 consecutive samples. Baseline noise was then removed.

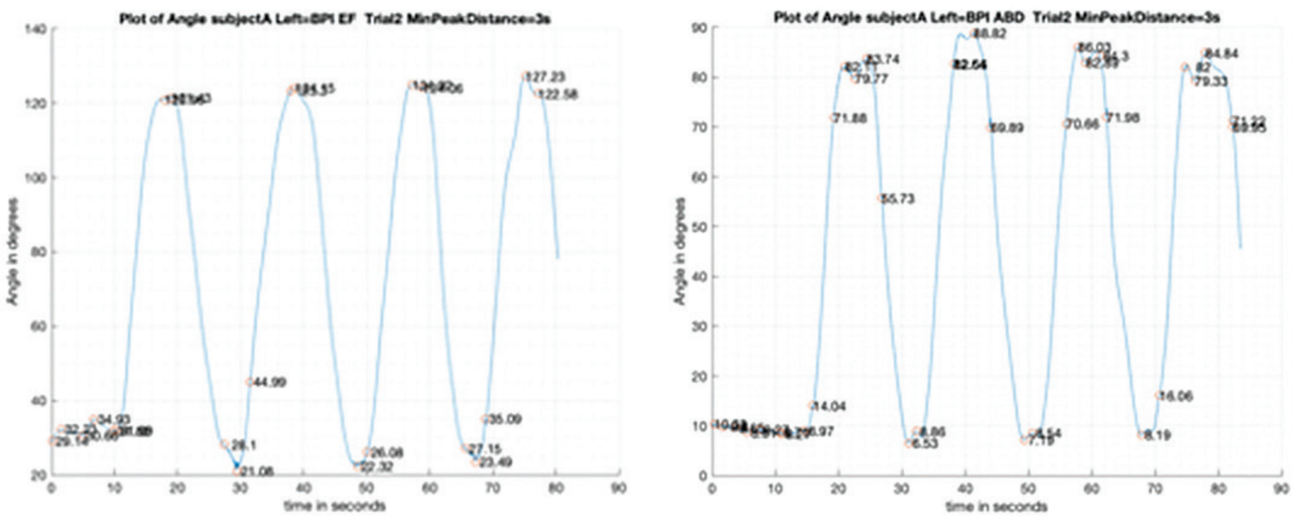

Figure 6. Example of plotted angular waveform of ROM showing the maximum values as peaks and minimum values as troughs.

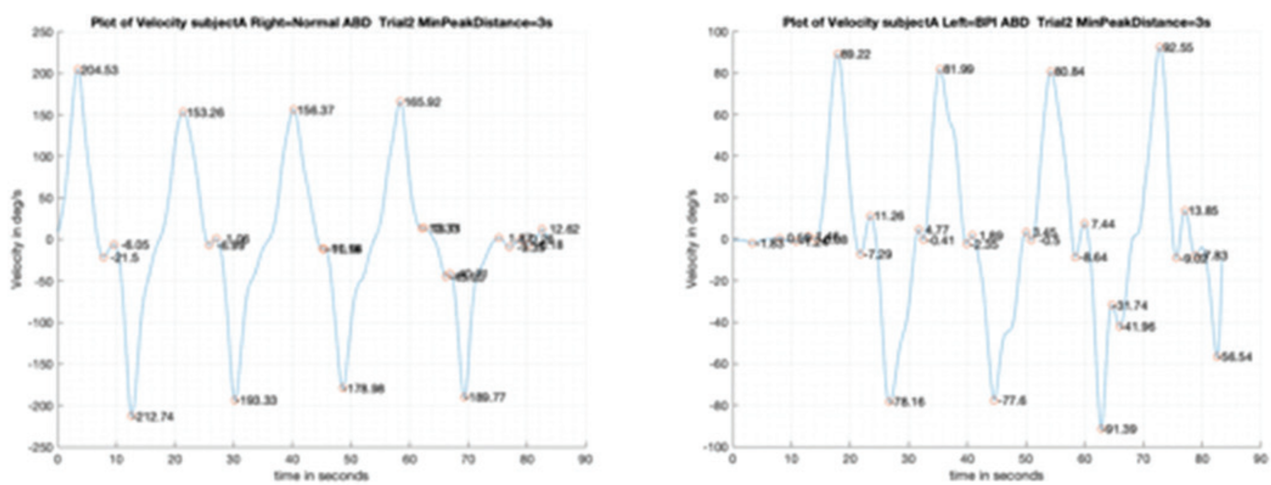

Figure 7. Example of plotted angular waveform of velocity showing the maximum values as peaks.

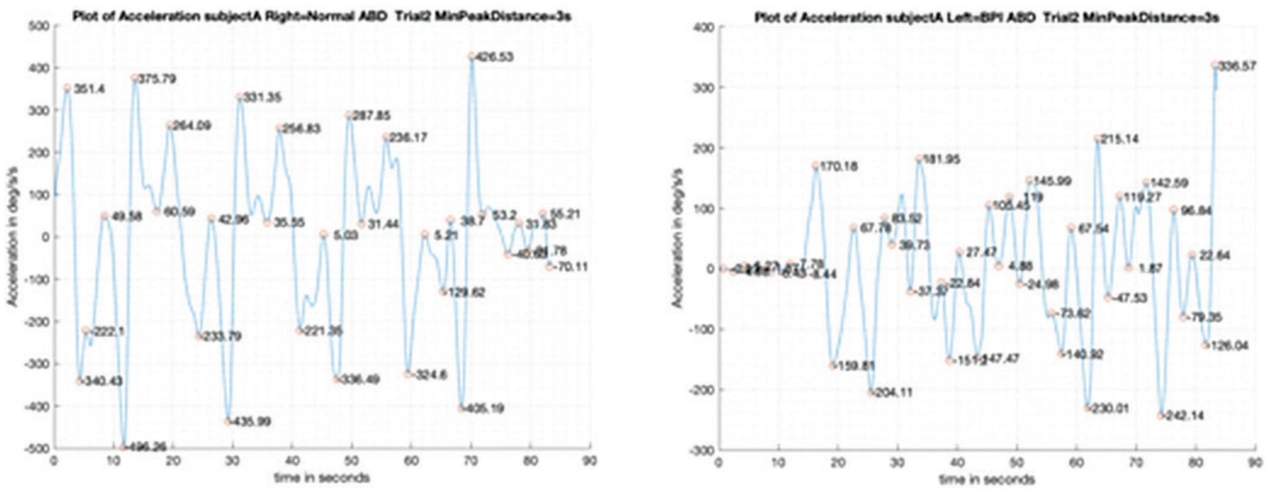

Figure 8. Example of plotted angular waveform of acceleration showing the maximum values as peaks.

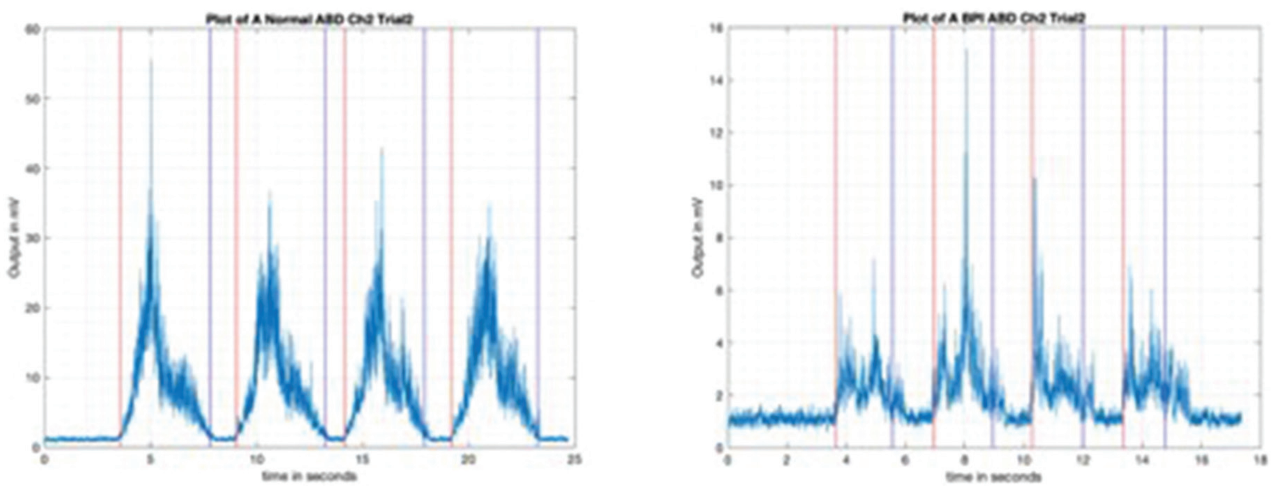

Figure 9. Example of EMG signals filtered and rectified, divided into cycles by the onset *(red verticals line)* and offset *(blue vertical line)* times.

EMG Cycle Normalization

The dataset was normalized to percent cycle for plotting and further analysis. Since each trial is composed of four repetitions of the same movement and a three-second recording at the relaxed state, a user interface with keyboard control was developed using MATLAB software to acquire the activity cycles. The software displays the current EMG trial and labels the calculated onset and offset times. Keyboard controls allowed the user to select the start and end of activity cycles using the calculated onset and offset times as reference (Figure 9). Once the selection is complete, the parsed data set is grouped by participant, condition, and task (Figure 10), and summarized to a single graph (Figure 11).

For each involved muscle for every task, for every repetition, and each trial, the following were recorded for each extremity: root mean square (RMS, expressed in mV), peak EMG signal magnitude (mV), and peak activation time (%).

Post-trial selection criteria

Some data were excluded from analysis due to noisy acquired EMG. This results to a failure to acquire the onset and offset times needed for cycle normalization.

EMG Amplitude Normalization

No amplitude normalization was done for the EMG samples. Filtered and rectified EMG values in millivolts were used for analysis.

Reliability of EMG Data

The intraclass coefficient (ICC) with confidence interval of 95% was computed to evaluate the intra- and inter-class reliability of the filtered EMG data. ICC values lower than 0.60 are described as "poor reliability, those from 0.60 to 0.79 as "good reliability," and those greater than 0.80 as "excellent reliability."[37]

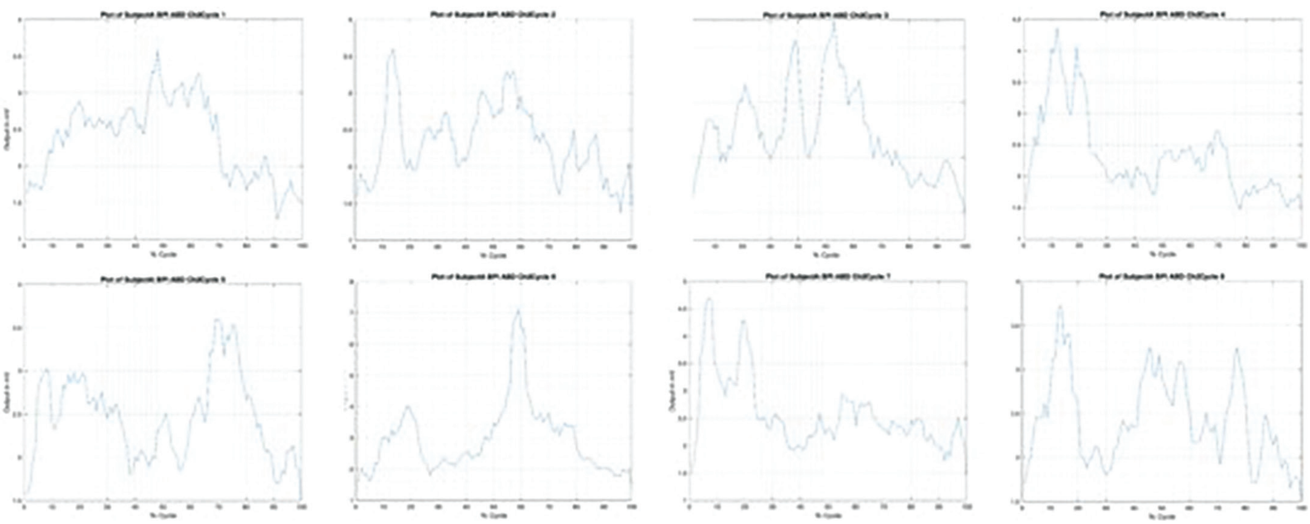

Figure 10. Example of eight repetitions of a task completed in 2 trials that are shown as 8 separate waveforms divided into cycles, expressed as 0-100% in the x-axis, with raw data filtered and normalized. The cycles are based on the onset and offset times previously identified, data at onset time at 0% to the data at offset time at 100%.

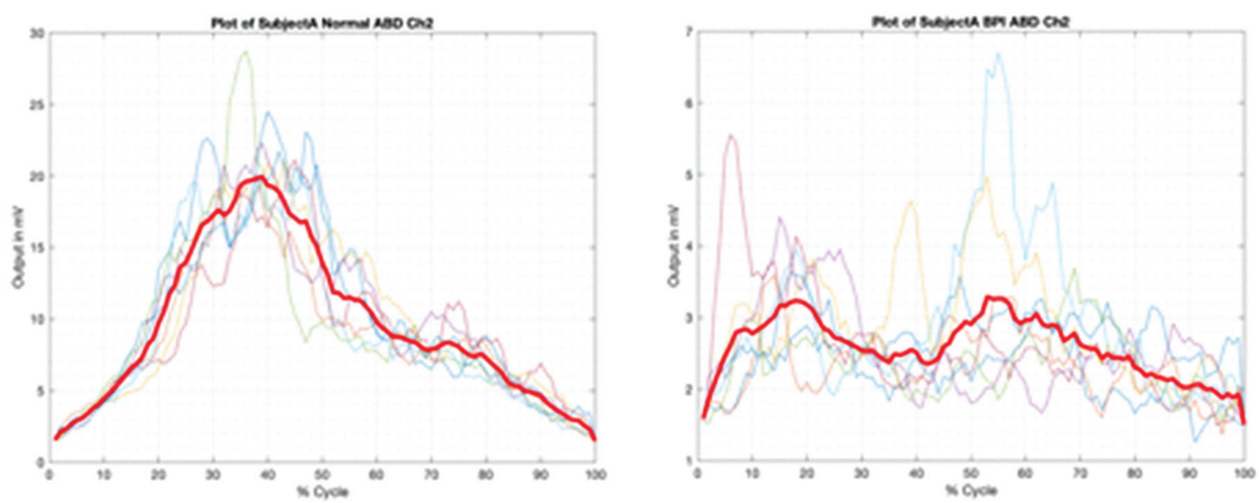

Figure 11. Example of summarized EMG data in waveforms. Each colored thin line represents a cycle, while the thick red line represents the linear envelope that is the average of all the cycles.

Statistics Used

Baseline characteristics of included participants were encoded in Microsoft Excel. The recorded measurements from KINECT and the EMG were summarized by their means and their corresponding standard deviations. The normality of the data was checked using the Shapiro Wilk test (level of significance $p<0.05$). Unpaired t-test was used to determine significant differences for all parametric data and Mann-Whitney U-test was used for non-parametric data. The level of significance was set at $p <0.05$.

The methods used in this study is summarized in the diagrammatic workflow (Figure 12).

RESULTS

Table 1 summarizes the participants included in the study, including the time delay from injury to surgery, nerve involvement in their brachial plexus injury, DASH scores, and the surgery done. On clinical examination, among the 3 participants, Participant C had the best recovery while participant A had the poorest recovery.

Tables 2 to 7 summarize the data gathered for KINECT and EMG of the participants. The data for KINECT ER for all participants were discarded because the waveforms plotted were not interpretable. The maximum and minimum values for the computation of ROM were not consistent with the observed motion and the goniometer measurement. Since the data for velocity and acceleration were calculations based on the plotted degrees for ROM, these were also discarded.

Since the rotator cuff muscles were inaccessible, the surface EMG evaluation of ER was attempted by using the superficial anterior and posterior deltoid muscles to check if there were compensatory actions that could detected. The raw signals gathered however were noisy and uninterpretable using the algorithm set for post processing the data. The data gathered were also discarded.

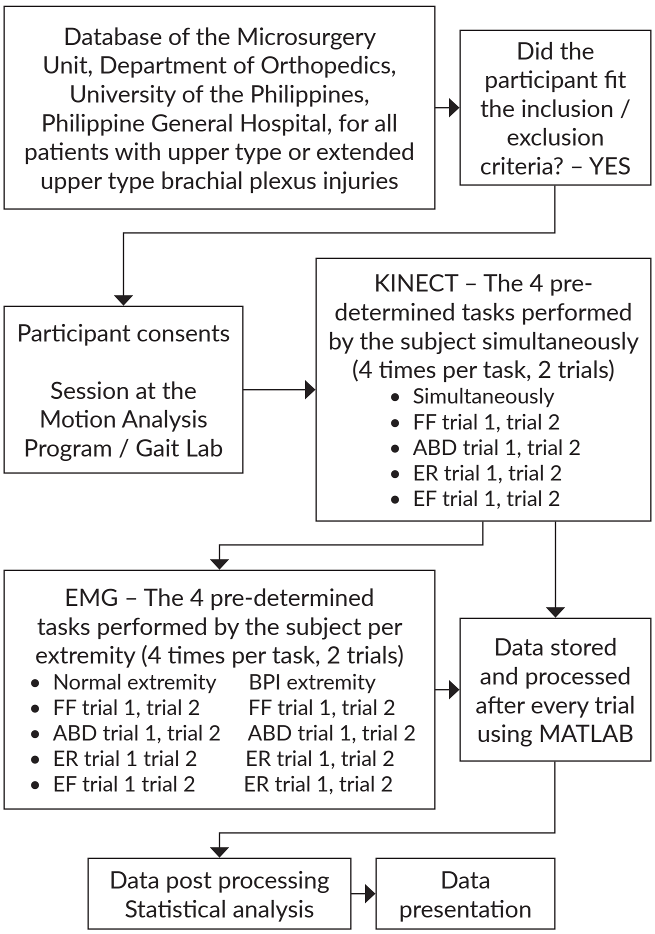

Figure 12. Diagrammatic workflow of the methodology.

The EMG data compared were non-normalized to be able to get the actual amplitude differences between the groups, expressed as RMS in mV. The normalized difference is the recorded peak of each muscle divided by the average contraction (RMS).

Only the EMG results with both sets of data for normal and BPI extremity available for comparison were included. For the rest of the muscles for the other tasks, either the normal extremity or the BPI extremity was only available, hence were excluded from the results and the rest of the analysis. The computed ICC served as a guide to caution data interpretation. The study included all interpretable data for EMG with available ICC, regardless of the reliability.

Participant A

The differences between the extremities were all significantly different except for FF velocity and acceleration, and the middle deltoid peak activation time for abduction. The values for maximum acceleration for the extremity with BPI for FF and EF were higher compared to the normal extremity (Figure 13).

The RMS and peak EMG showed significant difference between the two extremities – the normal extremity higher than the BPI extremity. The difference of the normalized data of EMG data showed a higher value of the normalized RMS for the extremity with BPI (Figure 14). The ICC for the middle deltoid were 0.94 and 0.16 for the normal and BPI extremities, respectively.

Participant B

The differences between the extremities for Participant B in KINECT were all statistically significant except for the FF ROM and velocity. For EMG, the RMS differences for all measured parameters (FF anterior deltoid and posterior deltoid, ABD middle deltoid, and EF triceps) were statistically significant. The peak EMG showed statistical difference for all parameters except for the anterior deltoid in FF. The triceps in EF for the BPI extremity showed a larger magnitude for both absolute and normalized values. Using ICC, the normal anterior and posterior deltoids in FF and normal middle deltoid in abduction had excellent reliability. The BPI posterior deltoid in forward flexion and normal

Table 1. Summary of the Participant Details

Participant	Age/ Sex	Mechanism of Injury	Delay to surgery (mo)	Involved Root	Surgery	Follow up (mo)	FF MMT	ABD MMT	ER MMT	EF MMT	DASH
A	61/M	MVA	14	C5C6	SAN-SSN, PRN-AXN, Oberlin I	45	3 / 5	3 /5	3 / 5	4 / 5	8.33
B	36/M	MVA	8	C5C6	SAN-SSN; PRN-AXN, Oberlin I, Tendon transfers: PT-ECRB; FCR-EDC; PL-EPL	61	4 / 5	4 / 5	4 / 5	4 / 5	51
C	31/M	MVA	8	C5C6	SAN-SSN, PRN-AXN, Oberlin II	60	5 /5	5 /5	3 / 5	5 /5	7

MVA – motor vehicular accident, SAN-SSN – spinal accessory nerve to suprascapular nerve, PRN-AXN – partial radial nerve to axillary nerve, Oberlin I – (partial ulnar nerve to biceps branch of musculocutaneous nerve), Oberlin II – (partial ulnar nerve to biceps branch of musculocutaneous nerve and median nerve fascicle to the brachialis motor branch of the musculocutaneous nerve), PT-ECRB – pronator teres to extensor carpi radialis brevis, FCR-EDC, flexor carpi radialis to extensor digitorum communis, PL-EPL pollicis longus to extensor pollicis longus, MMT – muscle motor testing

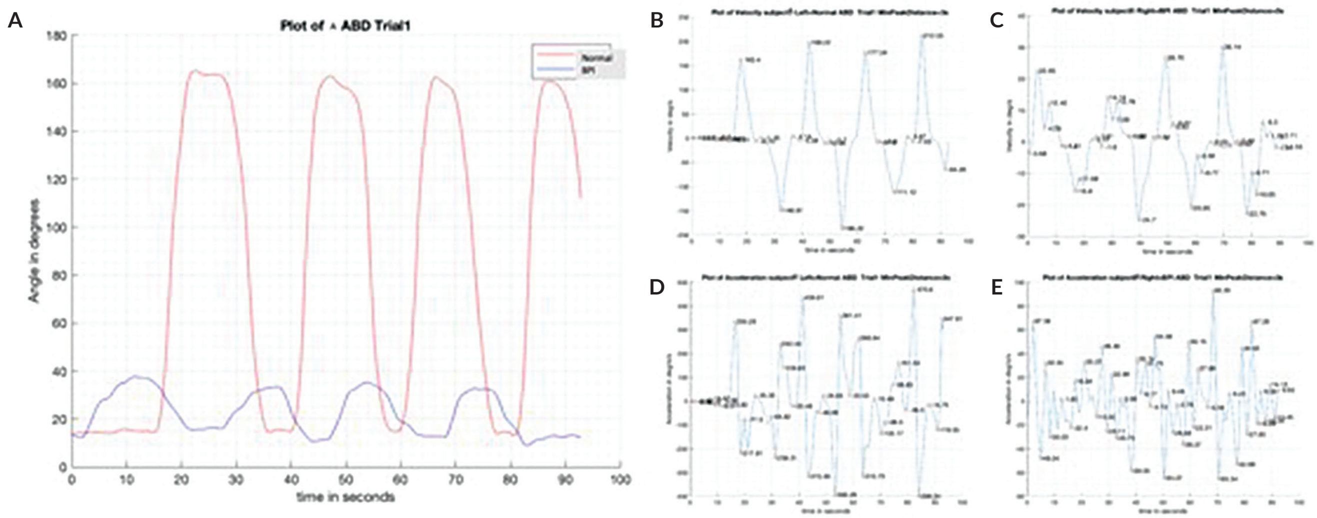

Figure 13. Summary of plotted KINECT data of Participant A for ABD in 1 trial showing **(A)** the ROM (red line – normal, blue line – BPI), x-axis time in seconds, y-axis angle in degrees, **(B)** velocity of normal extremity, **(C)** velocity of BPI extremity, x-axis time in seconds, y-axis velocity in degrees/second **(D)** acceleration of normal extremity, **(E)** acceleration of BPI extremity, x-axis time in seconds, y-axis angle in degrees/second^2. Negative values for velocity and acceleration indicate the extremity downward motion or adduction. Maximum and minimum values for velocity and acceleration are identified, maximum values for each cycle are recorded as peak results.

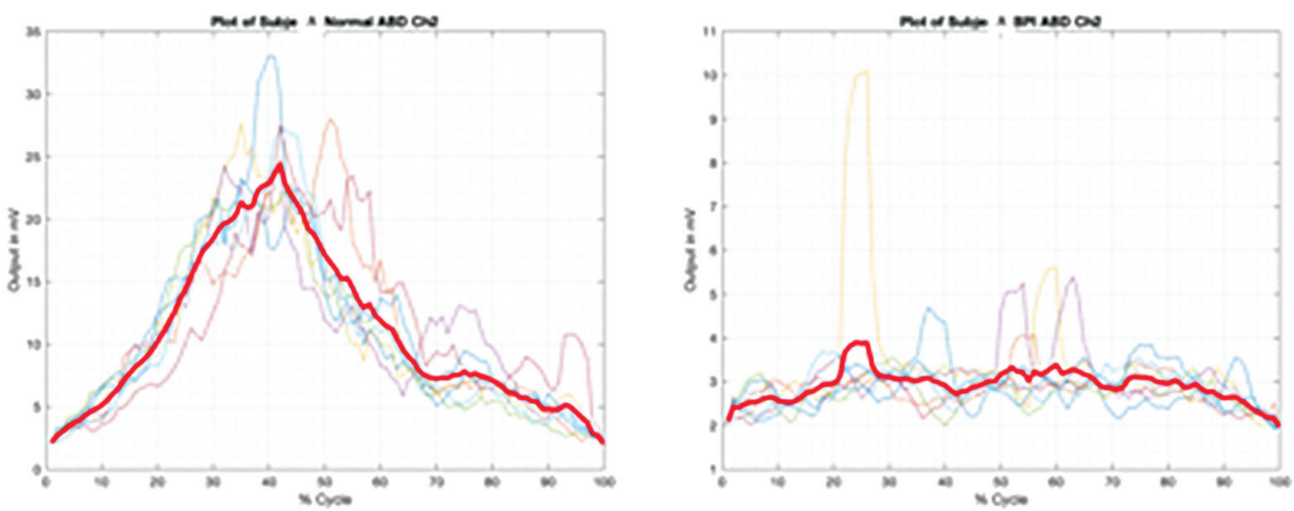

Figure 14. Summary of Participant A middle deltoid in ABD plotted EMG data, normalized to a cycle. The x axis is the percent cycle (% cycle) of the completed task. The y axis is the electrical signal in mV, rectified and filtered. Each thin line represents a repetition. The thick red line is the linear envelope of the samples representing the average of the cycles.

triceps in elbow flexion had good reliability. The other muscles in other tasks had poor reliability.

Participant C

The BPI extremity showed higher values compared to the normal extremity for all KINECT data. The normal extremity recorded higher EMG data of FF posterior deltoid peak activation time, all parameters for ABD middle deltoid, and EF biceps and brachioradialis peak activation time. For the difference of normalized EMG data, the posterior deltoid in FF and the middle deltoid in ABD maintained a higher value for the extremity with BPI. The differences for ABD velocities and accelerations and EF ROMs were statistically significant. For EMG, the differences for FF posterior deltoid parameters, ABD middle deltoid RMS and peak EMG signals, and EF brachioradialis peak activation times were statistically significant. Based on ICC, the biceps and brachioradialis for elbow flexion of the normal extremity

Table 2. Summary of KINECT Results of Participant A

Task		Normal		BPI		Difference	p value
		Mean	SD	Mean	SD		
FF	Goniometer (deg)	166		38		128	
	ROM (deg)	146.48	16.72	38.95	4.67	107.53	**0.01**
	Vel (deg/s)	178.96	61.05	48.68	7.76	130.28	0.064
	Accel (deg/s²)	758.22	126.07	1010.49	769.86	-252.27	0.56
ABD	Goniometer (deg)	168		28		140	
	ROM (deg)	146.63	3.344	24.21	2.63	122.42	**0.00**
	Vel (deg/s)	188.21	22.03	27.26	10.63	160.95	**0.00**
	Accel (deg/s²)	401.69	82.94	96.43	51.41	305.26	**0.00**
ER	Goniometer (deg)	85		26		59	
EF	Goniometer (deg)	148		24		124	
	ROM (deg)	111.28	5.06	14.23	1.21	97.05	**0.01**
	Vel (deg/s)	180.74	28.11	31.68	6.02	149.06	**0.00**
	Accel (deg/s²)	638.54	161.43	143.97	28.40	494.57	**0.00**

SD – standard deviation. P-value - significant p value <0.05 (in bold), set at 95% confidence interval. Vel and Accel parameters indicate peak velocity and peak acceleration recorded. ROM – range of motion. Difference – difference between the normal extremity with the extremity with BPI (means of recorded peak), negative values indicating higher recorded value for extremity with BPI

Table 3. Summary of EMG Results of Participant A

ABD		Normal			BPI			Diff	Diff Normal	P value
		mean	SD	ICC	mean	SD	ICC			
mid deltoid	RMS (mV)	12.72	0.56	0.94	3.27	0.68	0.16	10.06	-0.25	**0.00**
	peak EMG (mV)	51.05	11.31		11.19	12.28		35.79		**0.00**
	peak time (%)	39.68	8.24		56.73	18.39		-17.06		0.16

SD – standard deviation. P-value – significant p value <0.05 (in bold), set at 95% confidence interval. RMS – root mean square. Peak EMG – peak EMG signal magnitude recorded. Peak time – peak activation time, part of the data cycle (in percent, given that data cycle is expressed 0 – 100%) where peak EMG signal magnitude is found. Difference – difference between the normal extremity with the extremity with BPI, negative values indicating higher recorded value for extremity with BPI, or for peak activation time, a peak at an earlier time in the cycle. ICC – intraclass coefficient. Diff – difference between means of Normal and BPI extremity. Diff normal – difference of the normalized values (normalized values not shown)

had readings with poor reliability, the BPI biceps for elbow flexion had good reliability, while the rest of the muscles had excellent reliability.

Table 8 summarizes the KINECT and EMG results of Participants A, B, and C.

DISCUSSION

This experimental study evaluated the upper extremity function of participants using KINECT for kinematic data of ROM, peak velocity, and peak acceleration, and surface EMG for electrical signals of muscle contraction. Some results were discarded due to the noisy signals gathered making the data unreadable and thus uninterpretable. The results of the participants will be discussed in the context of the tools used and the errors encountered.

Participants

The three participants represent the varying extent of recovery of BPI reconstruction. Participant A had the poorest recovery while Participant C had the best recovery. The results were analyzed individually since a pooled analysis would have been greatly skewed. The DASH is a patient-rated functional outcome measure that is frequently used and has been validated for BPI patients.[38-43] A higher DASH score indicates a poorer functional status. The DASH score of Participant B, despite clinically performing better than Participant A, was highest among the 3 participants. On physical examination and checking which DASH domain was scored highly, this was associated with pain on performing functional activities.

The primary goal for patients with BPI is elbow flexion and the surgical procedures on these participants focus on this. Only Participant C had data to facilitate the comparison of both extremities for elbow flexion. Consistent with the clinical evaluation of the participant, both the KINECT and EMG data showed no significant difference between the normal extremity and the extremity with BPI. This demonstrates the excellent post operative recovery of the participant in elbow flexion. The clinical and KINECT data even showed a

Table 4. Summary of KINECT Results of Participant B

Task		Normal		BPI		Difference	p value
		Mean	SD	Mean	SD		
FF	Goniometer (deg)	164		80		84	
	ROM (deg)	131.70	31.56	101.22	13.86	30.48	0.10
	Vel (deg/s)	277.60	109.56	180.36	81.96	97.24	0.19
	Accel (deg/s²)	1657.96	385.43	891.52	175.75	766.43	**0.02**
ABD	Goniometer (deg)	180		72		108	
	ROM (deg)	167.38	6.50	77.96	2.568	89.42	**4.31E-08**
	Vel (deg/s)	175.89	24.37	86.13	10.66	89.76	**0.00**
	Accel (deg/s²)	358.18	66.01	187.02	32.45	171.17	**0.00**
ER	Goniometer (deg)	48		42		6	
EF	Goniometer (deg)	138		88		50	
	ROM (deg)	119.29	2.73	97.98	5.81	21.31	**2.95E-06**
	Vel (deg/s)	131.21	17.37	100.22	21.07	30.99	**0.01**
	Accel (deg/s²)	406.50	166.79	239.55	70.91	166.96	**0.01**

SD – standard deviation. P-value - significant p value <0.05 (in bold), set at 95% confidence interval. Vel and Accel parameters indicate peak velocity and peak acceleration recorded. ROM – range of motion. Difference – difference between the normal extremity with the extremity with BPI (means of recorded peak), negative values indicating higher recorded value for extremity with BPI

Table 5. Summary of EMG Results of Participant B

		Normal			BPI			Diff	Diff Normal	p value
		mean	SD	ICC	mean	SD	ICC			
FF										
ant deltoid	RMS (mV)	7.78	0.18	0.89	3.03	0.22	0.38	4.74	0.76	**0.00**
	peak EMG (mV)	19.62	0.72		5.34	2.07		14.28		0.09
	peak time (%)	45.64	7.58		48.26	38.26		-2.62		0.99
post deltoid	RMS (mV)	11.14	0.74	0.95	2.46	0.04	0.79	8.68	1.62	**0.00**
	peak EMG (mV)	39.95	7.6		4.84	0.27		35.11		**0.00**
	peak time (%)	46.98	6.87		40.89	11.23		6.08		0.09
ABD										
mid deltoid	RMS (mV)	11.3	0.32	0.96	2.64	0.32	0.4	8.67	0.18	**0.00**
	peak EMG (mV)	38.53	8.37		8.52	3.14		30.01		**0.01**
	peak time (%)	39.07	5.42		53	22.36		-13.92		0.73
EF										
triceps	RMS (mV)	2	0.12	0.64	3.02	1.20	0.12	-1.01	-1.04	**0.04**
	peak EMG (mV)	4.09	0.23		9.31	3.39		-5.22		**0.01**
	peak time (%)	46.41	10.42		51.58	22.98		-5.17		0.95

SD – standard deviation. P-value – significant p value <0.05 (in bold), set at 95% confidence interval. RMS – root mean square. Peak EMG – peak EMG signal magnitude recorded. Peak time – peak activation time, part of the data cycle (in percent, given that data cycle is expressed 0 – 100%) where peak EMG signal magnitude is found. Difference – difference between the normal extremity with the extremity with BPI, negative values indicating higher recorded value for extremity with BPI, or for peak activation time, a peak at an earlier time in the cycle. ICC – intraclass coefficient. Diff – difference between means of Normal and BPI extremity. Diff normal – difference of the normalized values (normalized values not shown)

greater ROM for the BPI extremity compared to the normal extremity. This is similar to Webber et al.'s[44] findings in their patients with BPI, wherein they attribute the higher values of the extremity with BPI to compensatory maneuvers that the participants employ to perform a specific task. The higher kinematic values of Participant C for the BPI extremity could be reflective of these compensatory maneuvers, wherein the BPI extremity movement is not controlled and the other shoulder muscles are overcompensating hence an overshooting of movement. So, although the performed task is the same as seen in the range of motion, the manner by which this action is accomplished by the participant is different, as seen in the kinematic data. The KINECT data of Participants A and B further highlight the recovery of Participant C. The ROM,

Table 6. Summary of KINECT Results of Participant C

		Normal		BPI		Difference	p value
		mean	SD	mean	SD		
FF	Goniometer (deg)	165		155		10	
ABD	Goniometer (deg)	180		152		28	
	ROM (deg)	147.82	8.41	150.70	9.59	-2.88	0.44
	Vel (deg/s)	132.17	15.91	153.37	19.032	-21.20	**0.04**
	Accel (deg/s²)	237.28	38.04	327.72	78.33	-90.45	**0.00**
ER	Goniometer (deg)	39		0		39	
EF	Goniometer (deg)	138		150		-12	
	ROM (deg)	112.26	3.421	118.57	4.714	-6.31	**0.01**
	Vel (deg/s)	137.75	40.18	147.26	46.52	-9.53	0.65
	Accel (deg/s²)	267.46	148.86	358.07	46.52	-90.61	0.10

SD – standard deviation. P-value – significant p value <0.05 (in bold), set at 95% confidence interval. Vel and Accel parameters indicate peak velocity and peak acceleration recorded. ROM – range of motion. Difference – difference between the normal extremity with the extremity with BPI (means of recorded peak), negative values indicating higher recorded value for extremity with BPI

Table 7. Summary of EMG Results of Participant C

		Normal			BPI			Diff	Diff Normal	P value
		Mean	SD	ICC	Mean	SD	ICC			
FF										
post deltoid	RMS (mV)	4.48	0.82	0.84	14.34	1.15	0.91	-9.86	-0.72	**0.00**
	peak EMG (mV)	12.24	3.90		49.56	10.23		-37.32		**0.01**
	peak time (%)	70.74	14.88		41.37	14.46		29.38		**0.00**
ABD										
mid deltoid	RMS (mV)	19.38	0.68	0.96	13.46	0.73	0.92	5.92	-0.04	**0.00**
	peak EMG (mV)	66.04	4.99		46.4	6.3		19.63		**0.00**
	peak time (%)	50.73	5.82		41.91	10.84		8.82		0.1
EF										
biceps	RMS (mV)	15.41	19.99	0.2	45.3	26.21	0.74	-29.89	1.49	0.07
	peak EMG (mV)	99.56	123.44		225.01	81.07		-125.45		0.26
	peak time (%)	49.12	24.74		42.68	12.35		6.44		0.79
brachio radialis	RMS (mV)	25.06	27.73	0.52	29.22	1.00	0.93	-4.16	0.44	1.086
	peak EMG (mV)	93.11	88.74		95.61	9.56		-2.49		0.97
	peak time (%)	58.43	8.68		39.42	12.87		19.01		**0.01**

SD – standard deviation. P-value – significant p value <0.05 (in bold), set at 95% confidence interval. RMS – root mean square. Peak EMG – peak EMG signal magnitude recorded. Peak time – peak activation time, part of the data cycle (in percent, given that data cycle is expressed 0 – 100%) where peak EMG signal magnitude is found. Difference – difference between the normal extremity with the extremity with BPI, negative values indicating higher recorded value for extremity with BPI, or for peak activation time, a peak at an earlier time in the cycle. ICC – intraclass coefficient. Diff – difference between means of Normal and BPI extremity. Diff normal – difference of the normalized values (normalized values not shown)

velocity, and the acceleration for EF of Participants A and B are all statistically significant, with the normal extremity having higher recorded values.

The middle deltoid in shoulder abduction yielded results for both KINECT and EMG for all participants. For the shoulder abduction BPI KINECT values, arranged from highest to lowest, Participant C ranked highest, followed by Participant B, and lastly, Participant A. If the assumptions for non-normalized data would apply to the EMG data for the three participants, wherein the setting is ideal and there are no confounders due to the raw signals, the results of the EMG also support the clinical evaluation. With none of the peak times in the cycle statistically significant, it may be concluded that the middle deltoid contracts maximally at the same part of the joint cycle, and that there are differences in magnitude and effort to accomplish the task. Participant C had generally higher EMG data for the BPI extremity compared to the contralateral extremity. This may be explained by muscle

Table 8. Summary of KINECT and EMG Results of Participants A, B, and C

KINECT/ EMG	Task (KINECT) / Muscle Tested (EMG)	Parameter	Participant A		Participant B		Participant C	
			Normal	BPI	Normal	BPI	Normal	BPI
KINECT	*FF*	Goniometer (deg)	166	38	164	80	165	155
		ROM (deg)	**146.48**	**38.95**	131.7	101.22	-	-
		Vel (deg/s)	178.96	48.68	277.6	180.36	-	-
		Accel (deg/s²)	758.22	1010.49	**1657.96**	**891.52**	-	-
EMG	*Ant Deltoid*	RMS (mV)	-	-	**7.78**	**3.03**	-	-
		peak EMG (mV)	-	-	19.62	5.34	-	-
		peak time (%)	-	-	45.64	48.26	-	-
	Post Deltoid	RMS (mV)	-	-	**11.14**	**2.46**	**4.48**	**14.34**
		peak EMG (mV)	-	-	**39.95**	**4.84**	**12.24**	**49.56**
		peak time (%)	-	-	46.98	40.89	**70.74**	**41.37**
KINECT	*ABD*	Goniometer (deg)	168	28	180	72	180	152
		ROM (deg)	**146.63**	**24.21**	**167.38**	**77.96**	147.82	150.7
		Vel (deg/s)	**188.21**	**27.26**	**175.89**	**86.13**	**132.17**	**153.37**
		Accel (deg/s²)	**401.69**	**96.43**	**358.18**	**187.02**	**237.28**	**327.72**
EMG	*Mid Deltoid*	RMS (mV)	**12.72**	**3.27**	**11.3**	**2.64**	**19.38**	**13.46**
		peak EMG (mV)	**51.05**	**11.19**	**38.53**	**8.52**	**66.04**	**46.4**
		peak time (%)	39.68	56.73	39.07	53	50.73	41.91
KINECT	*ER*	Goniometer (deg)	85	26	48	42	39	0
KINECT	*EF*	Goniometer (deg)	148	24	138	88	138	150
		ROM (deg)	**111.28**	**14.23**	**119.29**	**97.98**	**112.26**	**118.57**
		Vel (deg/s)	**180.74**	**31.68**	**131.21**	**100.22**	137.75	147.26
		Accel (deg/s²)	**638.54**	**143.97**	**406.5**	**239.55**	267.46	358.07
EMG	*Biceps*	RMS (mV)	-	-	-	-	15.41	45.3
		peak EMG (mV)	-	-	-	-	99.56	225.01
		peak time (%)	-	-	-	-	49.12	42.68
	Brachioradialis	RMS (mV)	-	-	-	-	25.06	29.22
		peak EMG (mV)	-	-	-	-	93.11	95.61
		peak time (%)	-	-	-	-	**58.43**	**39.42**
	Triceps	RMS (mV)	-	-	**2**	**3.02**	-	-
		peak EMG (mV)	-	-	**4.09**	**9.31**	-	-
		peak time (%)	-	-	46.41	51.58	-	-

Summary of results of Participants A, B, and C taken from Tables 2-7, with data presented as means. Values in bold indicate P-value – significant p value <0.05, set at 95% confidence interval. Cells with "-" means no data available. Vel and Accel parameters indicate peak velocity and peak acceleration recorded. ROM – range of motion. RMS – root mean square. Peak EMG – peak EMG signal magnitude recorded. Peak time – peak activation time, part of the data cycle (in percent, given that data cycle is expressed 0 – 100%) where peak EMG signal magnitude is found.

fatigue.[45] A greater EMG signal does not necessarily mean greater force, but could indicate that as muscle fibers become fatigued and produce less force, additional motor units are recruited to accomplish a task.

The kinematic data gives an objective analysis and describes the differences in velocity and acceleration to help understand how the extremity moves. The measured muscle contraction through EMG gives an objective parameter to the strength and describes the extent of reinnervation of the muscle after a brachial plexus injury.

The predetermined tasks were set to study the joints and the upper extremity movement in one plane. The results show the complexity of the upper extremity, despite simplifying movements, instead of, for example performing complex functional tasks. The extremity with BPI further illustrates this complexity and that the recovery is highly variable. According to Mosqueda et al.,[46] there is an inherent variability in upper extremity motion, accounting for the wide standard deviations seen in their data. Wang et al.[47] validated the use of the contralateral unimpaired arm as control for upper extremity kinematic analysis for children with obstetric brachial plexus palsy, however, they used the pediatric population and the sample size for their control was 40.

KINECT

The accuracy of KINECT in literature is very high with acceptable errors. Çubukçu et al.[48] compare KINECT with goniometer and report mean errors of ABD 0.33 deg, FF 2.83, and ER 0.50, while Steinebach et al.[31] show higher mean absolute errors of the KINECT with the goniometer with ABD 6.5 deg, FF 12.9 deg, EF 7.0 deg. Comparing KINECT with a laboratory motion tracking system, the root-mean-square errors for shoulder motion were up to ABD 7.5, FF 10.1, and ER 27.3.[32] Regarding validity, KINECT errors of FF 7.7 deg, ABD 6 deg, ER, 3.7 are the threshold to allow for use in clinical settings.[29] The CMC is also used to compare angular waveforms of the two system to describe the difference in measurement during activities of daily living. The accuracy of KINECT was recorded with the following values, ABD CMC = 0 69-0.82, FF CMC >0.87, and ER CMC <0.6.[30] An overall analysis of KINECT in terms of minimum detectable difference has shown ROM differences of 7° at the shoulder, and 11° at the elbow.[27] This study however was not able to reproduce the reported accuracy of KINECT in literature, and was not able to detect at all the motion in the transverse plane.

Different KINECT and participant positions have been recommended in literature to minimize errors.[49-51] Using a 3D motion capture system as gold standard, Cai et al.[49] showed how much the errors are with the different positions of the KINECT relative to the participant, up to FF 36.66 deg, ABD 9.38, ER 36.83, EF 28.32. The maximum errors of their study are more comparable to the results of this study. These positions were tried with a test subject prior to the sessions with the participant. On testing, the KINECT cameras set 1.5 m from the subject, 80 degrees apart and elevated 2 m and 45 degrees tilted to the subject, provided the most KINECT runs with the green coordinates on the screen (Figure 2) signifying that the KINECT sensors were registering the static and dynamic movements. The accuracy when compared to the goniometer was still not comparable to literature on testing but these positions were deemed best for the participants. On the actual sessions however, there were still a lot of frames not registering the joint coordinates, seen as absence of the green lines (Figure 3).

The sources of error using KINECT for kinematic data is described in literature and outlined by Yeung et al.[51] Self occlusion occurs when parts of the body are covered since the KINECT can only record the part that is nearest to the sensors. The article explains that despite having two cameras, the variations are not reduced by means of averaging the two sets of gathered data, because the values are often too far apart that it results in unmatched joints. Secondly, KINECT uses segments to plot the positions of the joint angles. These segments depend on bone length, seen as the segments in the KINECT screen, and this changes as the dynamic action occurs. Another source of error is artificial vibration wherein the KINECT system confuses coordinates when a segment nears and "vibrates" even on a nonmoving segment, causing aberrant and erroneous data. The authors successfully formulated an algorithm to correct these errors and artifacts. These may be looked into for the succeeding studies to address the accuracy issues of the study, especially since the program used to run the KINECT system for this study was only a modification of an original program designed for another similar project.

Surface EMG

The primary outcome for the EMG data was the average contraction of the muscle in a specific task, expressed in RMS. One of the objectives of the study is to determine if there is a significant difference in absolute value between the normal and affected extremity and by describing the recovery of the reinnervated muscles in terms of strength of contraction. The data to describe these need not be normalized.[52,53] This however should be interpreted with caution because non normalized data for surface EMG assumes that all external variables that could affect the surface EMG signals are exactly the same. These variables include proportion of slow and fast fibers, orientation of the fibers, muscle architecture and temperature, thickness of subcutaneous adipose tissue, electrode distance, size and placement, sex and age, skin impedance, and changes in posture.[12,15]

To further describe the difference between the two groups relative to one another, removing the effects of the external variables, the difference of the normalized data was included. It was not possible to normalize the data using the maximum voluntary isometric contraction (MVIC) because of participants might not be able to accomplish this due to the pathology of the extremity. Data were normalized instead to the peak value of each cycle.[52,53] This describes the difference in contraction relative to the maximum contraction reached for the specific task.

In general, the values for average muscle contraction expressed as the RMS and the peak EMG signal magnitude were higher for the normal extremity. Only Participant C had higher values for the extremity with BPI, but these were not statistically significant except for FF posterior deltoid RMS and peak EMG. Higher EMG signals may be due to increased recruitment of muscle fibers or due to muscle fatigue.[45] Participant C had significantly higher values for the posterior deltoid in FF, but this is confounded by the statistically significant difference in peak activation time. The EMG recorded higher signals at different times in the task cycle. The magnitude of muscle contraction helps describe the muscle contribution to the task, and gives an idea about the recovery of the reinnervated muscle.

The peak activation time describes the point of the cycle where the peak EMG magnitude is recorded. This is important to consider when interpreting data because a similar peak activation time facilitates a better comparison of the EMG magnitudes since it describes the EMG signal at the same point of the cycle. This means that the recorded signal describes the muscle activity that approximates the part of the task describing the same motion and behavior of the muscle in terms of length and kind of contraction. It also helps describe when the muscle is most active or when it contributes most during a task, or if there are advances or delays in peak muscle activation compared to the normal extremity. None of the available data showed this, except for Participant C posterior deltoid in FF as described earlier.

The negative value for the difference in normalized EMG data for Participant A middle deltoid in abduction (-0.25) may indicate that, with a higher normalized value for the extremity with BPI, although the RMS and peak values are less than the normal extremity, the muscle contracts at a higher magnitude on an average relative to its peak. This shows a greater relative exertion compared to the normal extremity to complete the task. The same may be true for Participant C, but to a lesser degree (-0.04). This is supported by the higher KINECT values of Participant C showing greater ROM, velocity, and acceleration, and on clinical examination.

For Participant C posterior deltoid in FF, although the difference of the normalized EMG data is -0.725, the data gathered for absolute contraction in RMS and peak EMG signals were at significantly different activation times in the cycle (70.74% for normal, 41.37% for BPI). Meaning, the posterior deltoid is described in different states of contraction, eccentric and concentric, reflecting the different position and motion of the extremity in the task cycle. This was verified in the video synced with the surface EMG system. This however still describes the contribution of the posterior deltoid to the total cycle and that it is much more active at an earlier time in the extremity with BPI.

Compensatory maneuver as a source of error in data collection

Participant A had the greatest difference in the measured clinical and KINECT parameters. Only the EMG for the middle deltoid for abduction was analyzed since the data for the extremity with BPI were discarded. This was consistent in the observation of the participant during the testing session wherein, although he was able to perform the tasks, he had the most difficulty among the three participants.

The compensatory maneuvers of some patients with BPI, wherein a greater contribution by the trunk, scapulothoracic, and humeralthoracic joints is present to facilitate a movement normally achieved by primary contribution of the normal glenohumeral joint has been documented.[44,46,54,55] For example, Mosqueda et al.[46] describes how patients with BPI would swing their arms around their backs to abduct their affected shoulders.

The difficulty of the participants to perform the tasks contributed to the difficulty in acquiring signals. For KINECT, the maltracking and the joint position inconsistencies made the plotted waveforms very erratic. This also caused added noise to the voltage recorded by the surface EMG, hence making the filtered data through the algorithm created erroneous.

Issues with External Rotation

ER was the most difficult task for the participants to perform with the BPI extremity. This may have contributed to the erroneous data gathered for both KINECT and EMG. Clinically, Participant C, despite having the best recovery overall, had no external rotation from the set neutral position. Participant B had the greatest range for external rotation but at only 42 degrees (nearly half of the expected normal range of 90 degrees). Given the relatively small arc of motion, this may have added to the KINECT's difficulty in acquiring data. The same may be true for Participant A with external rotation recorded at 26 degrees. In addition, while Participant C had some functioning external rotation, he would use gravity and his trunk to complete the task. He would occasionally hyperextend his trunk and swing it in rotation to help maintain the neutral to the externally rotated position. Participant C would usually employ this towards the end of the trial, owing most probably to the fatigue of the reinnervated muscle.

External rotation is mainly an action of the rotator cuff muscles. These muscles are deep and are beneath the more superficial trapezius and deltoid muscles. The surface markers for these muscles are currently not included in the SENIAM recommendations due to their deep location. The rotator cuff muscles would have been ideal to analyze for external rotation but a needle EMG would have to be used, which is beyond the scope of this study.

Limitations

This is an exploratory study with three participants. The accuracy of the KINECT and surface EMG is beyond the scope of this study. The program algorithm for KINECT used was a modification of a previous program originally created for a different study of the upper extremity. The surface EMG is a useful tool to evaluate superficial muscles and are not able to pick up signals from deeper muscles without noise from overlying structures. The deeper rotator cuff muscles were not examined.

Clinical Implications

KINECT and surface EMG provide more objective findings for outcomes of recovery of patients with BPI. These add the technical parameters of kinematics and electrical signals to the clinical evaluation. The movements performed by patients are further described through changes in position in terms of velocity and acceleration, and the muscle activity through signals are quantified. This can help identify specific problems and formulate targeted interventions – preoperatively, surgically, and postoperatively during rehabilitation – to maximize recovery and outcomes of patients. These tools can further be used to test muscle fatigue of reinnervated muscle and how it affects movement and patient function. More complex movements that replicate activities of daily living can be assessed in real time to evaluate how the patient uses the upper extremity in performing functional tasks. With a larger sample size, data of the normal upper extremity can be pooled and serve as a control for comparison of upper extremities with pathologic conditions.

CONCLUSION

This is an exploratory study which evaluated three participants with BPI and their long-term recovery after surgical reconstruction. The complexity of motion of the upper extremity, and the highly variable course of recovery of these participants in terms of kinematics and electrical activity of muscle contraction were demonstrated. The KINECT and surface EMG provide cost-effective, quick, and objective assessment of the upper extremity. These instruments provide measurements that further detail movement that can be used as basis for formulating individualized interventions. In succeeding studies, these may be used to evaluate participants performing functional activities where tasks are carried out in more than a single plane. Assessment alongside a functional outcome scale, such as DASH, can help delineate adaptive movements that patients employ to perform activities of daily living, to compare with the deficits picked up in singular plane ROM or in individual muscle group contraction.

A specific algorithm should be developed for the KINECT sensors to address the errors from the pathologic and compensatory effects of BPI in participants. This might address the problems encountered in the data gathered by the sensors. Surface EMG, although simple and noninvasive, has its limitation to evaluation of superficial muscles. A fine needle EMG would be more useful to evaluate external rotation of BPI patients especially since this action is one of the goals of their surgical intervention.

Once errors are addressed, more participants can be included in succeeding studies. Data from normal upper extremities can be used as control for comparing with BPI extremities or other upper extremity pathologies. A larger sample size may allow nerve transfer subtype analysis to assess outcomes based on the kind of surgery done. Repeat KINECT and surface EMG studies can be done to monitor interval changes, and subsequently modify and individualize the rehabilitation programs of patients.

Statement of Authorship

SOJG and EPE contributed in the conception and design of the work, acquisition, analysis, interpretation of data for the work, drafting the work and revising it critically for important intellectual content, final approval of the version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. CEJS contributed in the design of the work, interpretation of data for the work, revising it critically for important intellectual content, final approval of the version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. JRR contributed in the design of the work, acquisition, analysis, and interpretation of data for the work, revising it critically for important intellectual content, final approval of the version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. RPDL contributed in the acquisition, analysis, and interpretation of data for the work, drafting the work and revising it critically for important intellectual content, final approval of the version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Author Disclosure

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