MSc in Biomedical Engineering

Kinematic analysis of compensation movements of upper limb amputees and able-bodied individuals during grasping movements

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1 Acknowledgement

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2 Abstract

Upper limb prostheses users make compensatory movements to be able complete daily tasks. The primary compensation occurs from the next distal joint nearby the amputation. For transradial prosthesis users, the main compensatory movements often occur because of limited degrees of freedom and lack of control in the prosthetic wrist. Compensatory movements have been associated with musculoskeletal complaints (MSC), overuse injuries, and repetitive strain injuries (RSI), which are serious issues that may have long-term and chronic effects on a patient. This study aimed to investigate the kinematic analysis of compensation movements of transradial amputees compared to able-bodied individuals during grasping movements and performing Clothespin Relocation Test (CPRT). The study included kinematic analysis of the shoulder abduction-adduction, elbow flexion-extension and upper and lower trunk lateral bending. Nine able-bodied individuals and two transradial prostheses users participated in the study. Both prosthesis users had over two years of experience with the device and use it daily. The device that the amputees used was i-Limb Quantum, Össur. The CPRT was divided into two different assessments, where the participants performed an upward and downward assessment. Moreover, six various analyses were performed for both assessments; the comparison of the right and hands hand of able-bodied subjects and both prostheses users, a comparison of not affected and affected side of prostheses users, and a comparison of able-bodied subjects and prostheses users. The project cooperated with Össur hf (Reykjavik, Iceland and Livingston, United Kingdom).

3 Introduction

3.1 Upper Limb Amputation

Amputation is when a limb, such as arm or leg, is partially or completely removed from the body. In 2005 the population of amputees was 1.6 million, predictions show that the population may double by the year 2050 in the United States. One of the reasons for the increase may be associated with the diabetes epidemic that will be responsible for amputation in some individuals. It is known that the risk of amputation increases with age, with greatest risk above age of 65 years. [1]

Upper limb amputation is less common than lower limb amputation, resulting in 35% of upper limb amputation and 65% of lower limb amputation. Additionally, man are more likely to lose their limb than woman, resulting that 69% of man and 31% of woman population undergo amputation. [2]

The main reason for upper limb amputation is trauma, accounting for 80% of acquired amputation. The trauma occurs in man aged between 15 and 45 years. Second reason that causes the most of upper limb amputation is cancer/tumor and vascular complications of diseases. However, the reasons for amputation can be several, indications that may cause amputation are:

- Trauma beyond repair
- Irreparable loss of the blood supply
- Malignancy
- Severe contracture
- Infection
- Burns
- Thermal/electrical injury
- Frostbite
- Peripheral Vascular disease
- Complications from diabetes
- Cancer/tumor
- Accidents
- Congenital deformities etc. [1]

Congenital deformities or amputation is when a child is born without part of a limb which may be caused by blood clots forming in the fetus, cancer, mutation of gene expression or trouble of embryogenesis etc. [3] [4] Moreover, upper limb amputation has several levels and amputations are named by the level of amputated limb, see **Figure 1** Levels of upper limb amputation and residual limbs.. [5] Amputations in ascending order are:

- Transphalangeal
- Transmetacarpal
- Transcarpal
- Wrist disarticulation
- Transradial
- Elbow disarticulation
- Transhumeral
- Shoulder disarticulation

- Forequarter amputation

The most common upper limb amputation is transphalangeal, accounting 78% of all cases. It is important to mention that for any amputation the goal of the surgeon is to save all feasible tissue. While limb functionality is correlated with limb length [1] this surgical goal does not always align with prosthetic prescription. For example, in the case of transradial amputation a shorter transradial length can facilitate fitting a wrist device and/or an overall shorter prosthesis which is better tolerated in terms of weight and symmetry with the sound side.

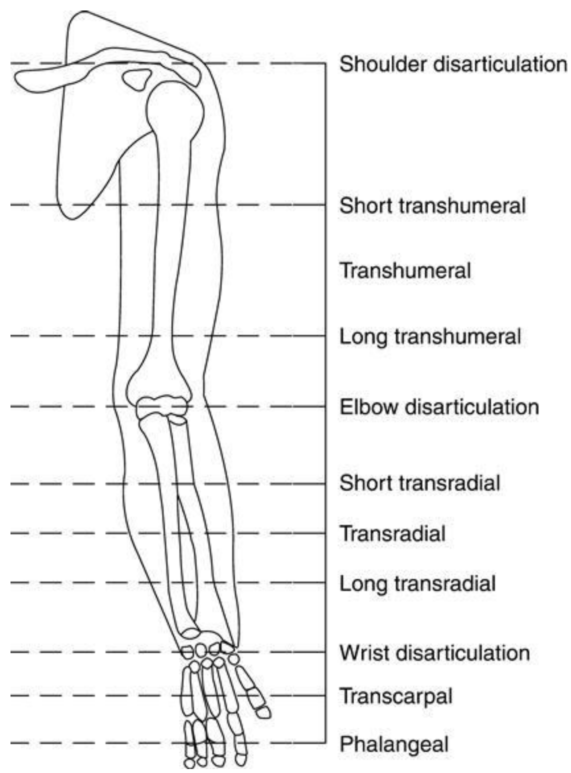

Figure 1 Levels of upper limb amputation and residual limbs.

Upper limb amputation can cause some complications such as phantom limb pain, residual limb pain, edema, contracture formation, body asymmetry, skin breakdown and neuroma. Phantom limb pain is a feeling of pain or sensations that amputee may experience in the "missing limb". The pain is most likely neuropathic and requires a treatment. It has been reported that decreasing edema and sensitivity can be helpful in reducing phantom limb pain. Additionally, electrical stimulation such as transcutaneous electrical nerve stimulation is used to treat phantom limb pain, it includes high-volt pulsed galvanic stimulation. Another treatment method used to treat the pain is mirror therapy. In the therapy the amputee is holding the sound hand in front of a mirror and the amputated limb is hidden behind the mirror. Among upper and lower limb amputation the phantom limb pain is estimated from 40 to 80% of amputees. Another complication is the residual limb pain, it is the pain in the stump that remains after an amputation, likely to be musculoskeletal due to remodeling of the hand and requires treatment, such as wound care and medications. Moreover, the amputation of the limb might cause edema. It is localized swelling that occurs in residual limb after trauma and mishandling of tissues during surgery. The treatment includes massages, compressive dressings etc. Contracture formation is another factor that might cause complications of the surgery, it is deformation and hardening of joints caused by musculoskeletal condition that affect muscles, tendons or other tissues. This complication has a long-term effect on the body. The treatment includes stretching and strengthening to preserve muscle bulk. Moreover, when patient does compensatory movements in function and gait due to weight distribution changes is called body asymmetry which is another complication. The compensatory movements will be described in more detail in Chapter 3.4. Complication of skin breakdown occurs when there is poor wound healing, bleeding, infection, edema and poor dressing techniques on the affected side. Lastly, neuroma occurs when a mass of nerves and soft tissue forms as nervous tissue remodels, which can be painful. The treatment might include medications for neuropathic pain or nerve blocks. [1] [6] [7]

3.2 Prostheses

Upper limb amputation is a serious globe issue. Like mentioned before the increasing population creates a need for progress in technicality and control of prosthesis. [3] Upper limb prostheses have a high rejection rate, or 20% to 40%, for example due to difficulties of control and lack of functionality. It is suggested that early fitting with prosthesis after amputation, rehabilitation and training can decrease the rejection rate. [8]

Prostheses are used to restore as much as possible the functions of the absent body part. However, the device will never fully replace the missing limb. Today prostheses offer solutions from cosmetic to body powered prostheses or even advanced myoelectric prostheses. Additionally, the devices have been developed to have greater degrees of freedom (DoF) to allow the users to move more freely. [3]

Body powered prosthesis are used with active control and require manual work. The device is known for moderate cost, silent action, light weight, durability, reliability, sensory feedback (position of the terminal device) and simple operational mechanism. [9]

The meaning of word myoelectric is technically muscle electric, the term “myo” comes from Greek language and means muscle. Myoelectric prostheses use biological signals to control movements of the device, where electromyogram (EMG) electrodes measure the action potential or the muscle electricity on the surface of the skin’s limb. The action potential or the muscle electricity are produced by contracting muscles. Additionally, there are several types of surface electrodes, such as gel-type and dry-type. Normally, the device includes two electrodes that are on the surface of the skin and obtain signals form two broad agonist/antagonist positions, for example the flexor and extensor compartments of the forearm, which allow opening and closing of the hand. [3]

One of myoelectric hands worth mentioning is i-Limb® form Össur. Össur is a global leader in innovative prosthetic devices. The company offers four different solutions, i-Limb® Ultra titanium, i-Limb® Quantum, i-Limb® Access titanium and i-Limb® Access. All i-Limbs are made for transhumeral, transradial and wrist prostheses users. The i-Limb Quantum, see **Figure 2**, is known for being the only myoelectric hand that changes grips with gesture. [10]

Figure 2 i-Limb® Quantum, Össur.

It is enabled by moving the device in one of four directions to assess the desired grip. Each finger is independently motorized, and thumb has a powered rotation feature with manual override. The digits are made of titanium and increase 50% in carry load. The device has 30% more grip force and 30% speed boost to enhance natural motion, strength and functionality. One of the key features of the myoelectric hand is the electronically rotating thumb with manual override. The thumb automatically switches between lateral and oppositional grip patterns for optimum grip. Another key feature is Vari-Grip™ which provides additional grip strength when applied. Additionally, the device allows selection up to 36 different grips, both preprogrammed and customized to suit user daily activities. Moreover, it includes Auto-Grasp™ feature, which prevents objects from slipping out of grasp. The device has two applications, Biosim™ and My i-Limb™ for setup and personalization of grips features and has multiple covering options. The i-limb is available in four different sizes, from extra small to large. [10]

3.3 Upper Limb Movements

The upper limb consists of three main regions, arm, forearm and hand. The arm is located between the shoulder and elbow joints and consists of single bone humerus. The forearm is located between the elbow and wrist joints and consists of two paired bones, the ulna (medially) and the radius (laterally). The hand is located distal to the wrist and has the base of eight bones, where each is called carpal bone. The hand has palm which is formed by five bones where each is called metacarpal bone. Finally, the fingers and the thumb include a total of 14 bones, where each is called phalanges bone of the hand. Overall, there are 60 bones in both upper limbs, 30 in each. [11] See **Figure 3** for upper limb and shoulder structure. [12]

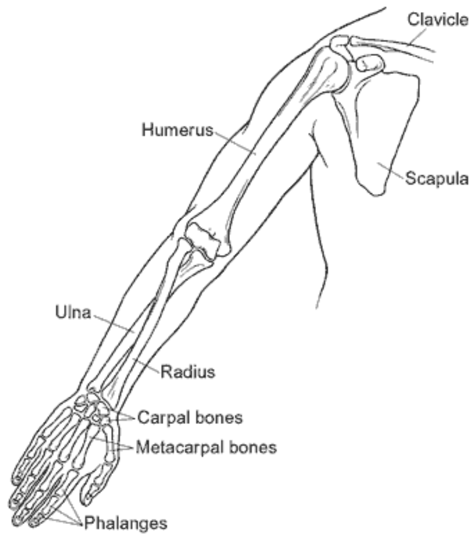

Figure 3 Upper Limb and Shoulder Structure.

Upper limb has complex structure and movements. It is important to mention that upper limb movement are associated with trunk movements. [13]

3.3.1 The Trunk

The spinal column is in effect the central pillar of the trunk and has three main segments: cervical, thoracic, and lumbar segments. Overall, there are 31 segments in the spine. The cervical region consists of seven cervical segments (C). The region is closest to the head and, the spine gives the head support. The thoracic region consists of 12 thoracic segments (T). This is the largest region of the spine, it is displaced posteriorly by the mediastinal organs, mainly the heart. The lumbar region consists of five lumbar segments (L). It is located under the thoracic region. It supports the entire upper trunk and its weight. Additionally, it resumes a central position. Lastly, the spine has the sacrococcygeal segment (S) and coccyx region at the end. [14] See **Figure 4** of trunk structure. [15]

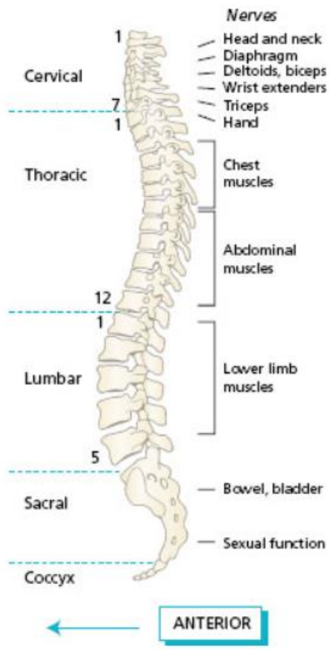

Figure 4 Trunk structure.

The trunk has the ability to move in 1) flexion-extension, 2) lateral flexion or bending, 3) axial rotation and 4) circumduction, see **Figure 5**. The flexion occurs while bending forwards, and extension while bending backwards from the upright position. The lateral flexion occurs while bending the trunk to the side. The axial rotation occurs while twisting the trunk right or the left. Finally, the circumduction is combination of all the movements mentioned. [15]

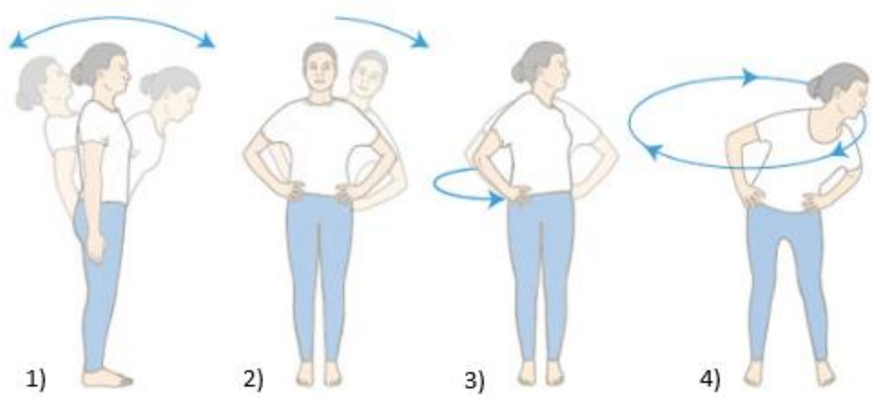

Figure 5 Trunk Movements. 1) Flexion-extension 2) Lateral flexion/bending 3) Rotation 4) Circumduction.

The lateral flexion of the trunk occurs in coronal plane, see **Figure 16**. The range of lateral flexion can be measured on radiographs taken from the front. As the baseline for the measurement the lumbosacral articular surface is used, the upper surface of the first vertebra. However, clinically those measurements are not accurate. However, the global range of lateral flexion of the lumbar spine (L) goes up to 20°, of the thoracic spine (TH) up to 20°, of the cervical spine (C) up to 35-45° and the total range of flexion from sacrum to cranium is 75-85° of each side (T), see **Figure 6**. [14]

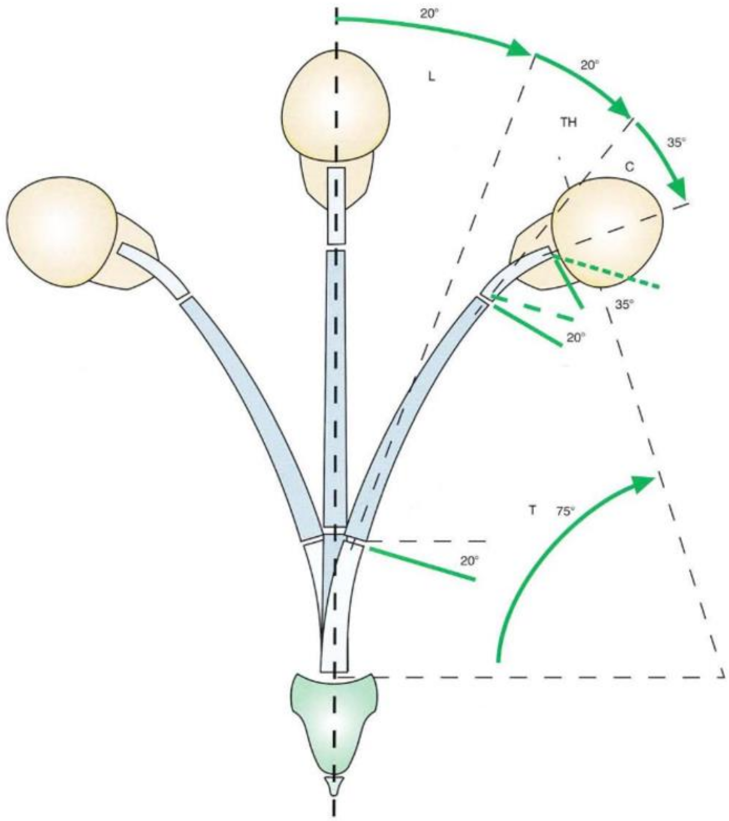

Figure 6 Global ranges of lateral flexion of the trunk.

3.3.2 The Shoulder

The shoulder is the proximal joint of the upper limb. It has the most mobility of all the joints in the human body. The shoulder has three DoF which allow orientation of the upper limb in three planes of space that correspond to its three major axes: the transverse, anterior-posterior and vertical axis.

- **Transverse axis** – lies in the coronal plane, allows the **flexion-extension** movement which occur in a sagittal plane.
- **Anterior-posterior axis** – lies in a sagittal plane, allows the **abduction-adduction** movement which occur in coronal plane.
- **Vertical axis** – runs through the intersection of the sagittal and coronal planes, controls the flexion-extension movements, which occur in horizontal plane with the arm abducted to 90°.

Additionally, the **long axis of the humerus** allows voluntary and automatic rotation which are types of lateral and medial rotation. They can coincide with any of the three-axis mentioned before. The reference position of the shoulder is defined as the position where upper limb hangs vertically at the side of the body. The long axis of the humerus coincides with the vertical axis. However, when shoulder is in 90° flexion it coincides with the anterior-posterior axis and when it is in 90° abduction its long axis coincides with the transverse axis.

The extension of the shoulder is a movement of small range, it is up to 45°-50°. However, the flexion of the shoulder is a movement of great range, that is up to 180°. See **Figure 7** for shoulder flexion-extension. Additionally, when position of the shoulder is at 180° flexion, it can be defined as abduction at 180° associated with axial rotation. Adduction is only possible from the reference position only when it is combined with a movement of extension (adduction is minimal) or flexion (adduction can reach 30-45°), otherwise the movement is not mechanically possible due to presence of the trunk, see **Figure 8**.

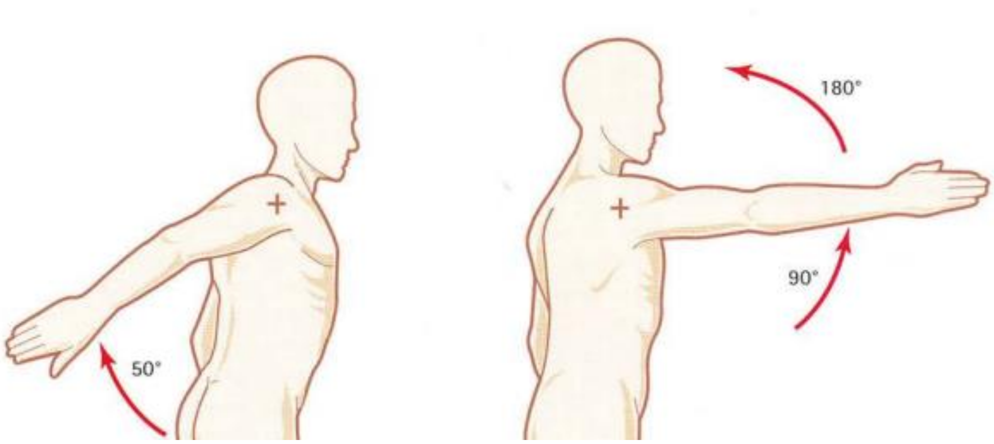

Figure 7 Shoulder extension (left figure) and flexion (right figure).

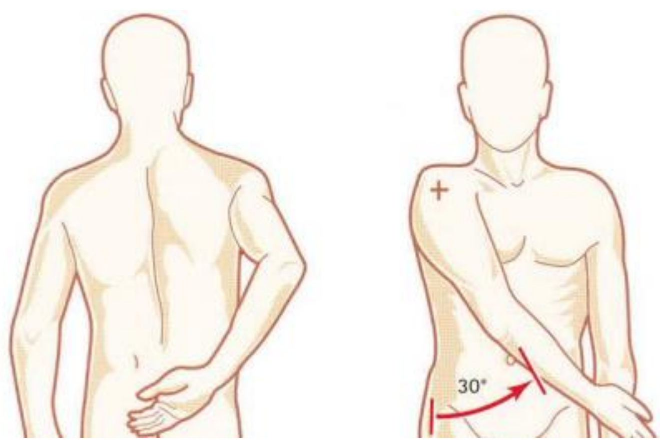

Figure 8 Adduction of shoulder among flexion (left figure) and extension (right figure).

The Abduction of the shoulder is the movement when the upper limb is moving away from the trunk, see **Figure 9**. Like mentioned before the abduction of the shoulder can reach 180°. It is worth mentioning that abduction can go through three phases:

- 0° to 60°- only shoulder joint is involved.
- 60° to 120°- recruitment of the scapulo-thoracic joint is involved.

- 120° to 180°- both shoulder and scapulo-thoracic joints are involved among flexion of the trunk of the opposite side.

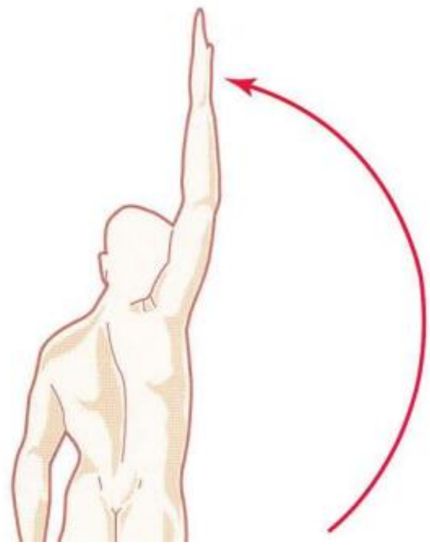

Figure 9 Shoulder Abduction.

Moreover, the shoulder allows lateral-medial rotation and horizontal flexion-extension, see **Figure 10**. The lateral rotation extends up to 80°. The medial rotation is up to 100-110°, when the forearm passes behind the trunk with the shoulder slightly extended. See **Figure 10** for lateral and medial rotation.

Figure 10 Lateral (left figure) and medial rotation (right figure).

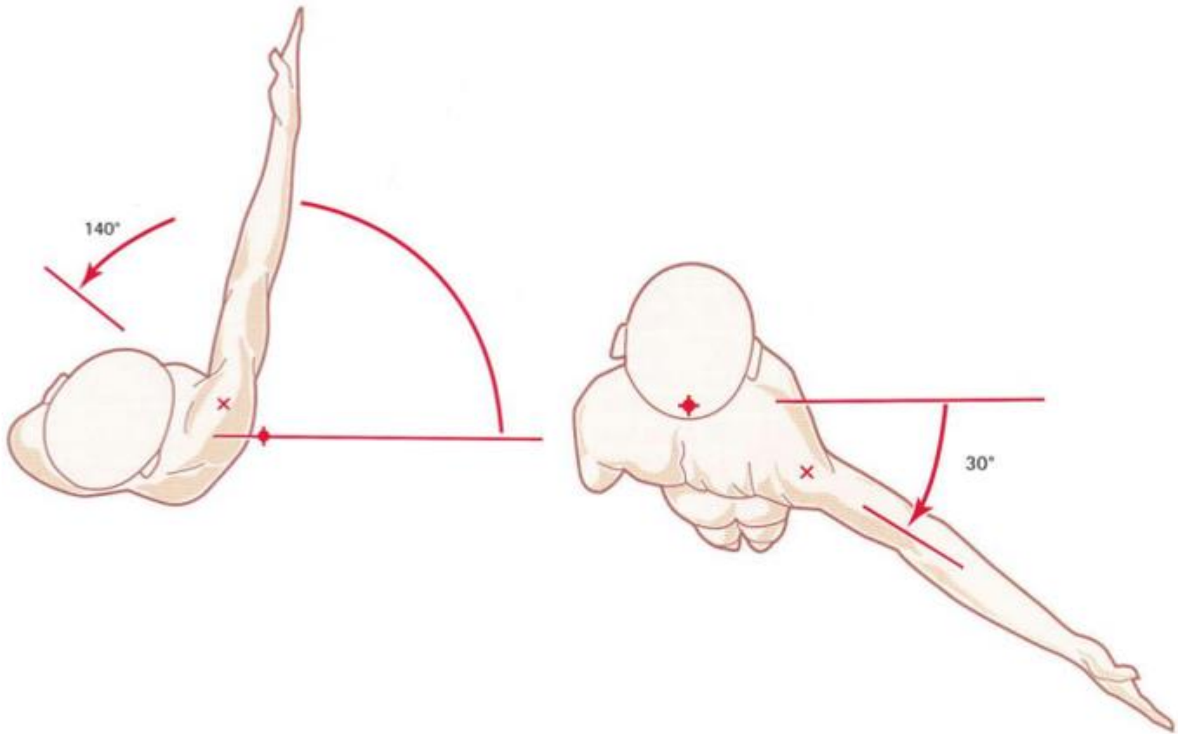

Figure 11 Horizontal flexion (left figure) and extension (right figure).

The horizontal flexion-extension takes place in horizontal plane, about vertical axis, see **Figure 11**. Both shoulder and scapula-thoracic joints are involved in the movements. The horizontal flexion is combined with adduction and has a range of 140°. However, the horizontal extension is combined with extension and adduction, and has range of 30-40°. [13]

3.3.2.1 Kinematics of The Shoulder

The joint coordinate system for the shoulder joint is complex, especially for flexion and abduction. The flexion and the abduction are defined in 2-D. An important factor worth mentioning is that flexion followed by abduction would give different results than abduction followed by flexion. Those terms are only defined relative to the thorax not the scapula, where the flexion of the shoulder is elevation parallel to the sagittal plane and abduction is elevation in the coronal plane. Therefore, many rotation orders are possible for the shoulder joint. However, differences are unavoidable where clinical definitions are consistent in 3-D. To solve this particular problem, the translations due to the joint displacement (q) of the humerus relative to the scapula (Gleno Humeral joint) with the respect to the scapular coordinate system were made. The definition of translated displacement for the GH joint is therefore, qx = anterior/posterior translation, qy = inferior/superior and qz = joint distraction. Therefore, International Society of Biomechanics (ISB) defined that the plane of elevation: 0° is abduction and 90° is forward flexion. Additionally, the internal rotation is positive and external rotation is negative in Y-X-Y order. [16]

3.3.3 The Elbow

The Elbow is a joint that links the upper arm and the forearm. It consists of single joint with single joint cavity and has two distinct functions: flexion-extension, see **Figure 12**, and pronation-supination. The flexion-extension or the movements of the hand towards or away from the body involves two joints the humero-ulnar and humero-radial joints. The pronation-supination involves the superior radio-ulnar joint, the forearm is moved around its long axis.

The extension of the elbow is the movement of the forearm posteriorly. The reference position is when the elbow is fully extended, and the extension is zero by definition. However, the joint allows hyperextension that ranges from 5° to 10°. The extension of the elbow is quantitated negatively. For example, the extension of -40° corresponds to an extension that falls short of the reference point by 40°. The minus sign gives information about the movement itself. The flexion is the movement of the forearm anteriorly. The range of active flexion is 140-145° and passive flexion has a range of 160°. [13]

Figure 12 Flexion-extension of the elbow.

Joint coordinate system and the motion for the elbow joint, where the forearm is relative to the humerus is in ZXY order and has corresponding definitions of the movements such as:

- Flexion (positive) and extension (negative).
- Pronation (positive) and supination (negative).

The coordinate system is recommended by International Society of Biomechanics (ISB). [16]

3.3.4 The Wrist

The wrist is the distal joint of the upper limb which has two DoF. However, when those two DoF are combined with pronation-supination or the rotation of the forearm the third degree of freedom is added. The wrist joint consists of two joints included with inferior radio-ulnar joint, the radio-carpal and mid-carpal joints. The radio-carpal joint is the wrist joint, it is located between the carpal surface of the radius and the proximal row of the carpal bones. The mid-carpal joint is located between the proximal and distal rows of the carpal bones.

The wrist has two main movements, flexion-extension and adduction-adduction or ulnar-radial deviation. The flexion-extension of the wrist is in sagittal plane. The flexion is the movement when the fingers are pointing away from the body, see **Figure 13**. The extension is the movement when the fingers are pointing towards the body, see **Figure 13**. Both flexion and extension have a range up to 85°. The adduction or the ulnar deviation is the movement of the hand towards the body. The range of adduction is 45°, it is the range between the reference point and the middle of the wrist. However, the abduction or the ulnar deviation is the movement of the hand away from the body. The range of abduction can reach up to 15°. See **Figure 14** of adduction-abduction/radial-ulnar deviation.

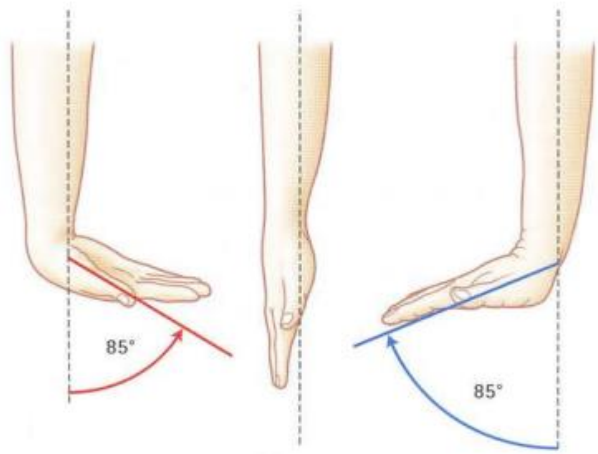

Figure 13 Wrist flexion-extension.

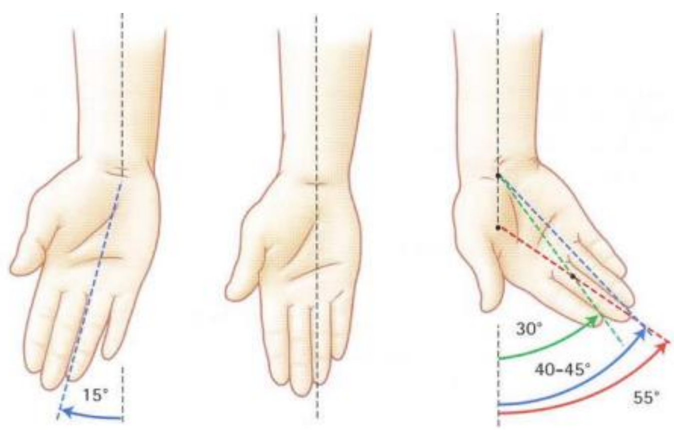

Figure 14 Wrist abduction-adduction/radial-ulnar deviation.

The wrist joint among the elbow joint allows pronation-supination of the wrist, see **Figure 15**. The supination is when the palm is facing superiorly, and the thumb is pointing away from the body. The pronation is when the palm is facing inferiorly, and the thumb is pointing towards the body. When the elbow is flexed at 90°, the range of pronation is 85° and supination is 90°. However, the total amplitude without any associated rotation, the range is close to 180°. The pronation-supination is one of the most important movements of the body. It is indispensable for the control of the orientation of the hand which allows the hand to assume the best position for grasping an object. The pronation-supination is the key movement for self-feeding. Additionally, it plays an major role in all actions of the hand, especially doing work. [13]

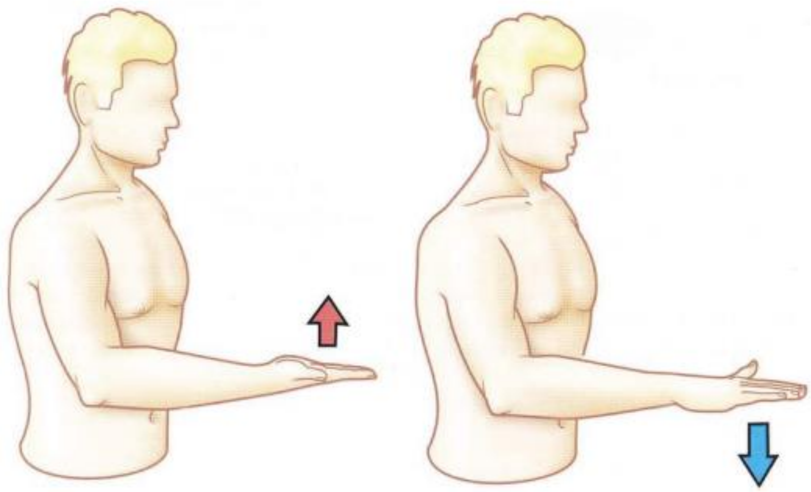

Figure 15 Supination-pronation.

3.4 Compensatory Movements of the Upper Limb

The upper body consist of multiple DoF, which allow appropriate selection of body movement to satisfy task requirements. Loss of upper limb causes loss of DoF due to pathology. For transradial amputees, the upper limb prostheses are not able to replace the active DoFs of the upper limb due to its complex structure and its movements. Upper prosthesis use might be challenging due to their difficult control for grasping and manipulation of daily life tasks. [17]

Upper limb prosthesis users in order to perform daily tasks make compensatory movements with both arms, affected and unaffected, and their trunk. Compensatory movements occur because of limited DoF in the wrist and the forearm. [18] [19]

Compensatory movement is when physical or neurological impairment changes way an individual performs a body movement or action. For example, individual with shoulder injury would not use his shoulder as much as normally. Instead, the individual would use his other joints to perform the task which would result in higher range of motion (ROM) in other joints. Compensatory motions can lead to increased stress in the muscles, overuse injuries and may cause musculoskeletal complaints (MSCs). Moreover, the same task can have different paths of compensatory movements for upper limb prosthesis users. Additionally, around 50% of upper limb amputees develop problems in the intact limb due to prosthesis use, such as MSC and repetitive strain injury (RIS). [20] [21]

To reduce the risk of shoulder pain and MSC disorders it is recommended to limit the amplitude of shoulder abduction in work related tasks. It has been suggested that unsupported arm elevation >60° for more than 10% of the workday or elevation >30° for more than 50% of the workday might increase the risk of disorders mentioned before. Additionally, more than 2h of shoulder abduction >60° during workday is associated with shoulder pain. [22]

Touillet et al[22] investigated Block to Box Test (BBT) among transradial hook prosthesis users. In the study two hooks are compared and unaffected arm. Greifer hook allowed 45° of ulnar and radial deviation and

Axon-hook allowed 45° of extension and 75° of flexion. The focus of study was to measure shoulder abduction and time with shoulder abduction >60° while performing BBT. The Greifer had 30% longer time with shoulder abduction >60° compared to Axon-hook and non-affected side, however, it wasn't statistically significant. The results might be not statistically significant due to small number of participants. Moreover, for shoulder abduction the differences between Axon-hook and non-affected hand were less than 1° and less than 1% of time percentage with shoulder abduction >60°. Overall, results of study suggest that transradial amputees fitted with hooks mainly use shoulder abduction as a compensatory movement during BBT. [22]

The control of wrist is an important requirement for successful usage of upper limb prosthesis in activities of daily life (ADL). Current prostheses have a lack of wrist control, either is the wrist able to rotate by using non affected hand or by myoelectric signal. However, controlling the upper prosthesis by myoelectric signal requires a lot of training and experience. Additionally, it requires mode switching control the proximal joint, both hand and wrist cannot be controlled simultaneously. Due to the lack of wrist control, prostheses users can develop different movement strategies, where some of them might result in compensatory movements. Prosthesis that allows wrist flexion/extension are available on the market and are suggested to be more beneficial, however, only few studies report the satisfaction rate with the device. Additionally, these require mechanical manipulation and no powered flexion exists at current time. [23] [24] [25]

Deijs et al[23] investigated differences between flexible and static wrist units in transradial prosthesis users. Higher satisfaction was reported with flexible wrist, where flexion/extension was available. Patients report that they were able to grab more objects pro-actively with their device and that handing objects was easier. Moreover, they felt more relaxed and less restricted movements of the hand among less awkward shoulder movements and less musculoskeletal complains. However, the functionality did not differ between the two wrist units. One of the reasons for not seeing the differences might be that the abundant DoF in the arm make compensation distributed over a series of joint angles and therefore hard to quantify in specific joint angle. [23]

Upper limb compensatory movements barely have a formal definition. Objective of study by Hussaini et al[21] was to identify and define compensation mechanisms for upper limb prosthesis users. In the study able-bodied and prosthesis users performed a set of bimanual activities. Compensatory types were divided into three different categories, different postures, ROM, and prepositioning.

Different postures, involves the adoption of new static posture to perform tasks, compared to able-bodied individuals. In this category the prosthesis user moves their body segment into new position, which is held constant throughout the task.

Range of motion is the increase or decrease in ROM of a joint or the segment. The change of rotation angle is visible compared to able-bodied individuals. Range of motion and different postures categories are different in way that different posture is when individual stays relatively constantly in the same posture throughout the activity. In the category, the movement has a dynamic difference.

Lastly, the prepositioning compensation category is the prepositioning the items in the workplace, which happens before the activity if performed. As example the fork is mentioned, a fork can be positioned in the prosthetic hand by the intact hand before eating a meal. [21]

The range of motion and the posture can be associated with musculoskeletal risks. Reaching the maximum ROM creates a stress in the joint (articular surface) and might lead to tendonitis. The prepositioning would be intended to reduce that risk. Those factors are important for the prosthesis training/therapy.

Additionally, there is a lack of publications about the skill level and angular joint parameters (RoM) in prosthesis users. Valevivius et al[26] investigated compensatory movements and skill level in body powered prosthesis users. Trunk flexion/extension or lateral bending was reported while performing tasks. On average there was 19 DoF difference from able-bodied population. Prosthesis users with higher skill level used trunk axial rotation rather than trunk lateral bending or flexion, which is visible in less skilled prosthesis users. Additionally, users with higher skill level had movement of flexion/extension closer to the physiological baseline. Findings suggest that increased skill level reduces compensatory movements in the trunk. [26]

Overall, studies suggest that limited range of motion of the prosthetic wrist, causes compensatory motions in the elbow, shoulder or trunk joints. It is most likely due to changed strategies of movement patterns. [17] [18] [19] [20] [22] [23] [27] [28] [29] [30] [31] [32] [33] [34] [35]

These behaviors should not be ignored, where compensatory motions could result overuse injuries in long term. Therefore, the rehabilitation process should ensure that patients get appropriate training. [28]

3.5 IMU and Xsens

An inertial measurement unit (IMU) is an electromechanical or solid-state device mostly know for motion measurements. It consists of gyroscopes, accelerometers and magnetometers, which is an array of sensors that allow motion capture. The system provides data about the motion by detecting linear acceleration and angular rate in about the X,Y and Z axes.

The gyroscopes, measures the angular rate which is an angular velocity around each axis. They measure short-term changes in orientation. Accelerometers, detect linear acceleration which is the change in angular velocity over time along each axis. The magnetometers are optional; however, they provide measurement of the magnetic field surrounding the system. Both accelerometers and magnetometers provide longer-term stability. [36] [37] [38]

Each sensor mentioned before, includes patented StrapDown Integration (SDI) algorithms. The algorithms are used to send the data to software, such as Xsens. Xsens is motion tracking technology and products that are based on IMU technology. The SDI data of motion is combined with biomechanical models of the human body, that has three planes; sagittal, frontal/coronal and transverse plane, see **Figure 16**. [39] It is done to obtain segments positions and orientations. The orientations are usually obtained by using fusion algorithm such as Kalman filtering to clean the signals from accelerometer, gyroscope and magnetometer. Moreover, to combine SDI data with the biomechanical model calibration is used. Therefore, the calibration estimates the proportions and dimensions of individual that is being tracked including orientations of each sensor with respect to the corresponding segments.

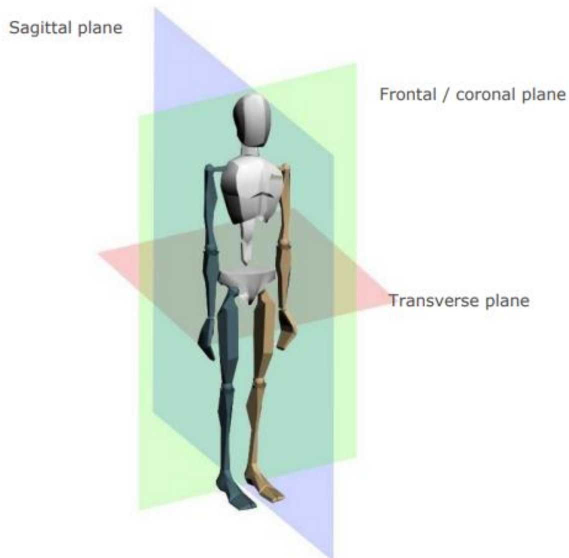

Figure 16 Xsens avatar: body planes

Calibration process includes scaling, sensor-to-segment and axes definition. The scaling is where the dimensions are obtained, by applying input parameters of the individual. Xsens allows detailed scaling of the individuals, where the parts of the body are measured. For example, length from toes to the hip etc. The minimal information acquired by Xsens in order to perform the calibration process are the height of the individual and foot length. Sensor-to-segment is used to align measurements from sensors to segments kinematics. It is done by using calibration method where the individual stands in N-pose and T-pose, see **Figure 17**. [38] Additionally, the individual walks a short distance back and forth for few seconds.

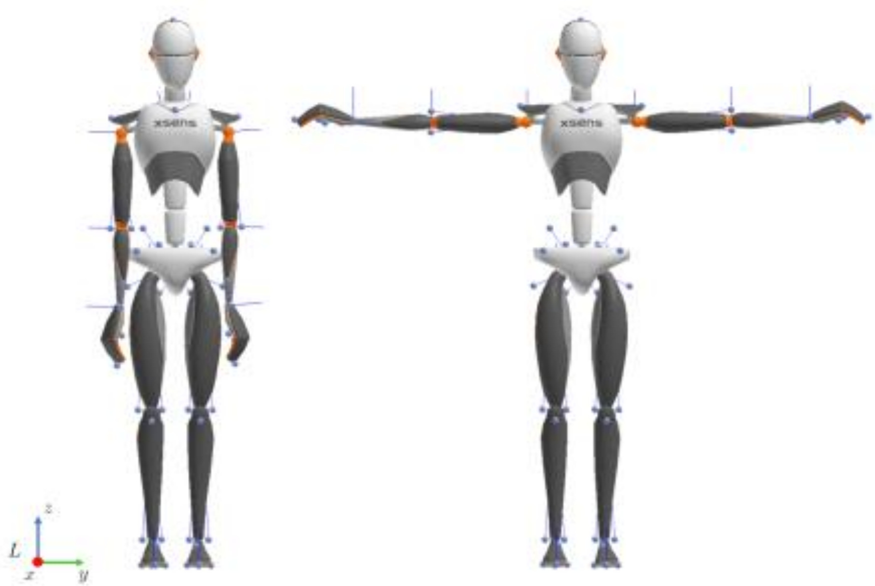

Figure 17 Xsens MVN avatar in calibration state. Left avatar is in N-pose and right avatar in T-pose.

The axes definition if used after completion of the sensor-to-segment calibration. The calibration is applied to the N/T-pose while the individual stands forward direction of the measurement environment, while the definition and origin (reference point at the right heel) of forward X direction of the local L coordinate system is being done.

Joint angles are an important metric when it comes to analyzing kinematic data. Xsens provides joint angles that are based on the definition of International Society of Biomechanics (ISB) for standardization. The Y-axis is aligned with the vertical, X-axes is pointing forward and Z-axes is pointing lateral in the Xsens coordinate system. Additionally, X is positive when pointing to the local magnetic North (red), Y according to right handed co-ordinates West (green) and Z is positive when pointing up (blue), see **Figure 17**. Moreover, the joint angles are firstly obtained by calculating differences between the orientation of the proximal segment and distal segment. Those calculations are converted to Euler angles which follow the recommendations of IBS, Grood and Suntay[41]. Each axis is associated with measurement of specific movement, Y-axes with internal/external rotation, X-axes with abduction/adduction and Z-axes with flexion/extension. It is important to mention that the names of the angles may be different for some joints, where some joints include dorsiflexion/plantarflexion, pronation/supination, lateral bending and/or axial rotation. [38] [40] [41]

Different biomechanical models can be used to fit the kinematic data from the wearable sensors. However, when full body sensor set is used with 17 sensors, the biomechanical model consists of 23 segments that are linked through 22 joints, see **Table 1** and **Figure 18**. Additionally, all of the joints have 3 DoF. Like mentioned before, the model is based on ISB and, Grood and Suntay[41] recommendations. [39] [41]

Table 1 All joints available in MVN.

	Joint Angle	Description (& Euler Sequence)
1	L5S1	Joint between the lumbar spine segment 5 and sacral spine 1 (ZXY)
2	L4L3	Joint between the lumbar spine segment 4 and lumbar spine segment 3 (ZXY)
3	L1T12	Joint between the lumbar spine segment 1 and thoracic spine segment 12 (ZXY)
4	C1Head	Joint between the cervical spine segment 1 and the head segment (ZXY)
Left and Right		
5	T4Shoulder	Joint between cervical spine 7 and the MVN shoulder segment
6	Shoulder ZXY	Shoulder joint angle between the MVN shoulder segment and the upper arm; calculated using the Euler sequence ZXY
7	Shoulder XZY	Shoulder joint angle between the MVN shoulder segment and the upper arm; calculated using the Euler sequence XZY
8	Elbow	Joint between the upper arm and the forearm. (ZXY)
9	Wrist	Joint between the forearm and the hand. (ZXY)
10	Hip	Joint between the pelvis and upper leg. (ZXY)
11	Knee	Joint between the upper leg and lower leg. (ZXY)
12	Ankle	Joint between the lower leg and foot. (ZXY)
13	BallFoot	Joint between the foot and the calculated toe. (ZXY)

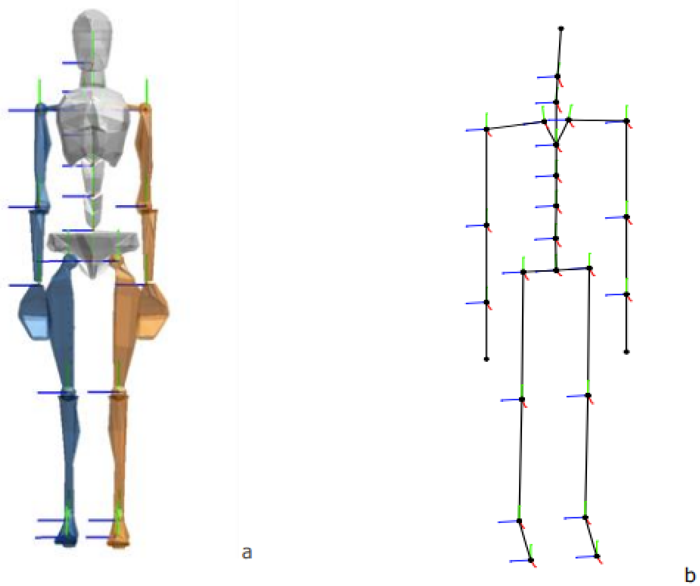

Figure 18 a) Segment coordinate system at each joint origin, to determine joint angles. b) Joint centers connected (x-axes: red, y-axed: green and z-axes: blue).

The aim of kinematics measurement systems is to help researchers and clinicians to understand human movements and their diseases, to improve the rehabilitations and/or the design of assistive devices performance. [42]

The calibration is used to track the kinematics of human joints. The calibration process is mostly done before the data collection and processing in inertial based motion tracking sensors. The calibration relates movements of body segments, mentioned before, to sensors measurements. The process of calibration can be done differently, the N-pose and T-pose can be used, the sensors might be placed on a flat surface, sensor-to segment alignment technique where the differences of orientation and sensor coordinates are computed, aligning the coordinate system or static anatomical position are assumed. The system responds by telling is the calibration is weak, poor, or good. Suggestion for additional accuracy of such system is to define a standard set of movements for the internal calibration of data processing resulting higher clinical relevance. Additionally, the IMU motion capture system does not have as restrictive environmental requirements, it is much cheaper and less time consuming when it comes to measurements. [43] [44] [45]

The optoelectronic measurement system is considered as gold standard measurement method that follows international standards (International Society of Biomechanics, ISB). The system is based on infra-red cameras, that allow tracking of 3D position of reflective markers placed on the subject. The calibration of such system is a limitation, it is caused by the length of camera calibration time, strict area of measurement among marker occlusions, which are usually required in laboratory environments. Those laboratories are expensive, non-portable and require a high level of technical expertise and time-consuming calibration. [43] [44] [46] [47]

Researchers question the accuracy of motion capture measuring systems. The accuracy of measurement system is an important factor to be able to understand human movements and behavior. [48]

Up to date there is a lack of publications of upper limb motion tracking, especially upper limb prosthesis users. However, for the lower limbs many publications can be found. The complicated movements and multiple redundant DOFs in the upper limb make motion tracking and analysis challenging. [43]

Like mentioned before, the optoelectronic measure system or optical motion capture system is concerned as a gold standard method. Few studies investigate kinematics movements and compare the gold standard system and IMU system. [42] [43] [48]–[53]

Wang et al[43] investigated motion analysis of able-bodied subjects using bypass prosthesis device using marker-based system (Vicon, Oxford, USA), IMU system (Xsens Awinda MTw, El Segunda, CA, USA) and markerless system (dual Microsoft Kinect V1s with iPI Recorder). Brace adaptor with a perpendicular handlebar was used at attach the i-limb Ultra (OSSUR, Foothill Ranch, CA, USA) to the able-bodied subjects. The prosthesis was attached to the brace with a medical offset of 15° from the subject's forearm. The grips of the device were controlled thought the TouchBionic my i-limb™ application. The subjects performed Target Box and Blocks Test (tBBT).

The results showed highest precision in the shoulder for IMU system. However, the elbow accuracy was not high, it might be influenced by the sensor placement. Moreover, IMU system had over all greatest stability, therefore the correlation, per the ICC metric. Those findings suggest that the IMU system is beneficial and may be the best for clinical monitoring purposes. [43]

Mavor et al[53] compared Xsens and gold standard method, optical motion capture system Vicon. In the study movements were measured with both systems. Reporting's confirmed that systems were positivity correlated. Differences between the systems were greater for upper limb, than lower limb. The root mean square error (RMSE) was greater for rapid motions and larger ranges of motions. [53]

Walmsley et al[49] systematics review observed a low error between wearable sensors and three-dimensional motion analysis (3DMA), the error was <5° for all DoF, using high level of customization to achieve smallest error as possible. [49]

Bai et al[50] investigated position accuracy between Vicon Cameras System and internal sensing system Xsens. The mean error for position tracking position between two systems was 0.99%. [50]

Fantozzi et al[51] suggested that the accuracy of the inertial magnetic measure unit (IMMU) might be affected by velocity, during a fast movement. Therefore, faster movements would cause a higher error between IMMU and stereo-photogrammetric system. Additionally, analysis of each joint was made separately in the study. Results showed that the shoulder had higher agreement between the systems than the elbow. [51]

Overall, wearable sensors are promising tool providing clinical information for upper limb measurements. [42]–[44] [48]–[55]

3.6 Objective

The population of amputees is constantly growing and is a serious global issue. Like mentioned before, the population of amputees in 2005 was 1.6 million, and it was predicted to be double by year 2050 in United States. The population has a wide range, from young to elderly people. Current technological solutions such as prostheses, do not replace the lost limb and its functions. Some features are challenging to replace, especially for the upper limb due to its complex structure and its movements. The upper body consist of multiple DoF, which allow appropriate selection of body movements to satisfy task requirements. Therefore, the loss of the upper limb causes loss of DoF due to pathology. Moreover, the upper limb prosthesis use might be challenging due to difficult control for grasping and manipulation of daily life tasks. [1] [3] [17]-[19]

Around 50% of the upper limb amputees develop problems in the intact limb due to prosthesis use. The problems are often associated with compensatory movements that prostheses users perform due to limited DoF in the wrist and the forearm, in order to complete daily tasks. The compensatory movements can lead to increased stress in the muscles, overuse injuries and may cause musculoskeletal complaints. Those are serious issues that can occur due to prosthesis use. Additionally, there is a lack of publications in that field. [20] [21]

Understanding the issues of current prosthesis is a step-in to direction of improvement of quality of life of prostheses users. Therefore, this project was developed to understand the current issues and differences in the movement between transradial upper limb prostheses users and able-bodied subjects performing Clothespin Relocation Test (CPRT).

The research question of the study is following:

1) Do transradial prostheses users show greater:
    a. Abduction/adduction motion in the shoulder compared to able-bodied subjects during the task?
    b. Flexion/extension motion in the elbow compared to able-bodied subjects during the task?
    c. Trunk lateral bending compared to able-bodied subjects during the task?

The hypothesis of the study is that compensatory movements or at least differences will be visible in the shoulder, elbow and trunk in transradial prostheses users subjects compared to able-bodied subjects.

4 Methods

4.1 Participants

A total of 12 subjects participated in the study. Ten of these subjects were able-bodied subjects and two were prostheses users. Out of ten able-bodied subject, one subject was excluded from the study due to wrong calibration in motion analysis. In able-bodied population, there were nine man and one woman. Out of able-bodied subjects six were right-handed and three left-handed. Both prosthesis users had their residual limbs at transradial level and were experienced with the prosthesis's device over 2 years. Both prostheses users used i-Limb®, Össur device in the study. See **Table 2** for participants characteristics.

Table 2 Participants characteristics.

Subjects	Age	Gender	Nature of Limb Absence	Level	Affected Side	Dominant Hand	Terminal Device	Frequency of Use
P01	41	M	Amputation	Transradial	R	R	i-Limb Quantum	4-8h/day
P02	42	M	Congenital	Transradial	L	R	i-Limb Quantum	8-12h/day
Able-bodied median	40	8M/ 1W	N/A	N/A	N/A	6R/3L	N/A	N/A

4.2 The Clothespin Relocation Test (CPRT)

The Clothespin Relocation Test (CPRT) was used as assessment for the participants in the study. The CPRT is a self-timed procedure that requires relocation of three clothespins between a horizontal and vertical rod, the numbers on each figure indicate the order in which the clothespins are moved, see **Figure 19**.

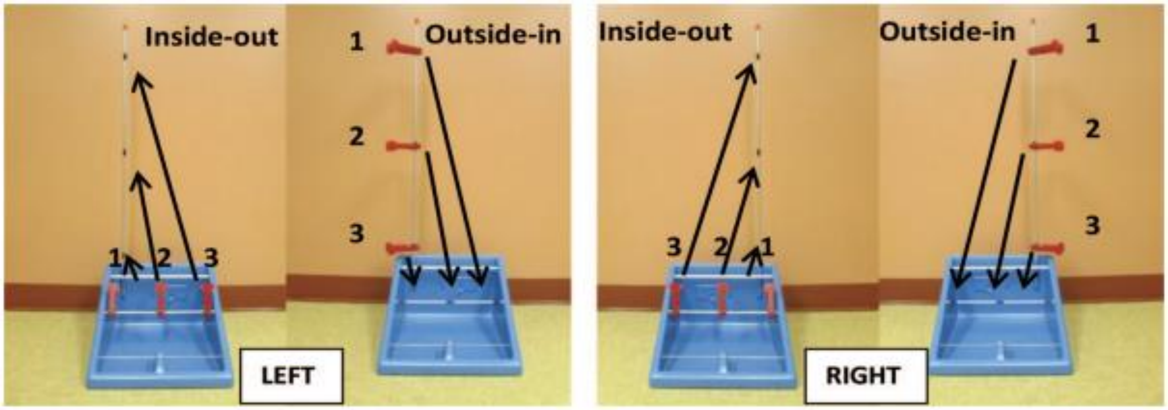

Figure 19 Clothespin Relocation Test (CPRT). Left hand assesment (left figure) and right hand assesment (right figure).

On horizontal and vertical rods were target locations that consist of electrical tape wrapped around at different locations, see **Figure 20** for set up.

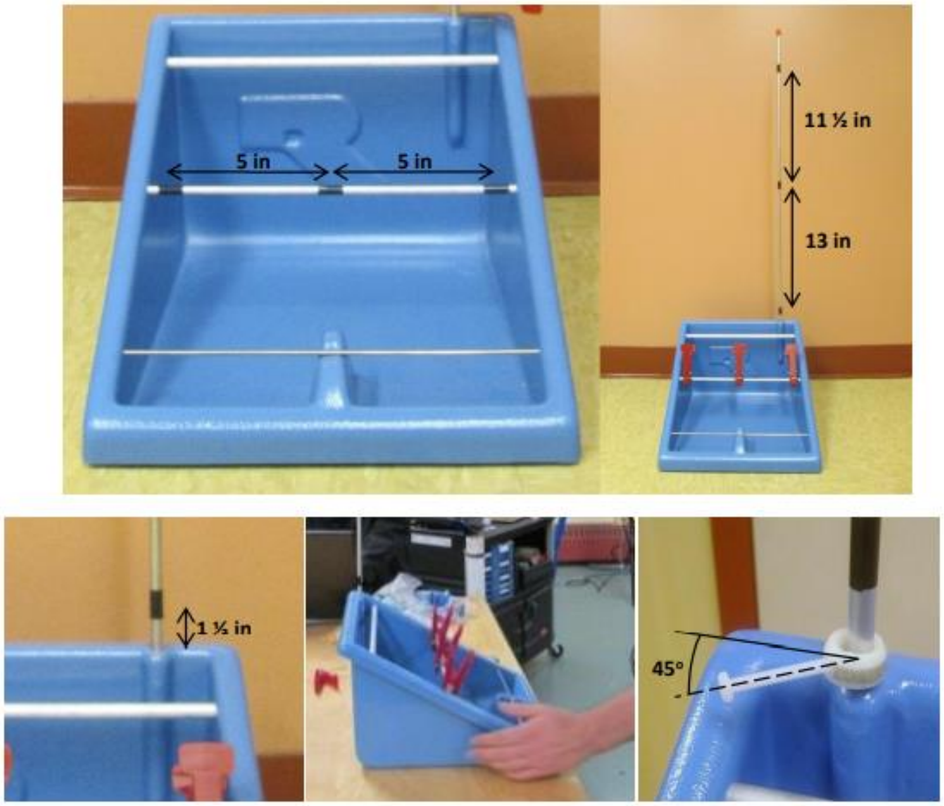

Figure 20 Standardized set up of CPRT.

The CPRT was placed on an adjustable table that was in line with the hips of participants, it was modified for each subject. The clothespins at horizontal rod were placed at 90°, and were fixed after each measurement, see **Figure 21**. When the clothespin reached the vertical rod, the clothespin was fixed to 45°, see **Figure 20**.

Figure 21 Clothespin are set at 90° before the upward trial.

The reason of choosing 90° of the clothespins for horizontal rod is due to simpler set up of the CPRT. Another reason is due to terminal device, if a participant would use a hook instead of hand, the user might push the clothespin down or rotate it towards the body. Overall, it is done for standardization. [21]

The subjects were introduced to the assessment and were allowed to use the strategy of choice to grasp the clothespin. The patients were not allowed to move their legs from the marked point on the floor. All subjects were allowed to practice an upwards and downwards assessment before starting the measurements. All participants did each assessment at least three times (upwards and downwards), with both hands.

4.3 Motion Capture

To record the kinematic data MVN Awinda, Xsens sensors among Xsens software were used. The sample frequency to record the kinematic data was set at 60 Hz. The system includes 17 sensors, see **Table 3** of correct placement of the sensors. Following sensors have a left and right side: foot, lower leg, upper leg, shoulder, upper arm, forearm and hand. [39] Each participant had his height and foot length measured to form proportional avatar in the software. Each patient went thorough calibration process, described in Chapter 3.5, see **Figure 17**. **Table 2** lists four joint and their motion angles that were analyzed. The lower trunk is a combination of joint L4-L3 and L1-T12.

Table 3 Locations of the sensors.

Location	Abbreviation	Optimal position
Foot	FOOT	Middle of bridge of foot
Lower leg	LLEG	Flat on the shin bone (medial surface of the tibia)
Upper leg	ULEG	Lateral side above knee
Pelvis	PELV	Flat on sacrum
Sternum	STERN	Flat, in the middle of the chest
Shoulder	SHOU	Scapula (shoulder blades)
Upper arm	UARM	Lateral side above elbow
Fore arm	FARM	Lateral and flat side of the wrist
Hand	HAND	Backside of hand
Head	HEAD	Any comfortable position

Table 4 Joints and motion angles.

Joint	**Description of Joints in Xsens**	**Movement**	**Positive Direction**	**Negative Direction**
Upper Trunk	T9-T8	Lateral Bending	Left Side	Right Side
Lower Trunk	L4-L3 and L1-T12	Lateral Bending	Left Side	Right Side
Shoulder	Right/Left Shoulder	Abduction/Adduction	Abduction	Adduction
Elbow	Right/Left Elbow	Flexion/Extension	Flexion	Extension

4.4 Data Analysis

The goal of the CPRT is to analyze the user's performance in controlled environment. The analysis includes both observational and time measures. The observational measure involves analysis of compensatory movements performed by subjects to complete the assessment. However, the time measure is analysis of the time to perform the assessment, which serves another metric to establish user's improvement over time. [21] In the study only observational measure was used. The joints and their movements that were analyzed are listen in **Table 4**.

The data analysis was performed in Matlab R2022b. The first step of the analysis was to load in three trials for both hands and each subject, separately for assessment of clothespin being placed upwards and downwards. Next step of the analysis included movement detection, for each trial. The movements were detected using plot of shoulder abduction/adduction and Xsens recording for additional visualization. Therefore, four ranges were detected for each participant, trial, hand and assessment. For upward assessment the ranges of the movements were defined as the movement where subject picks up the clothespin on horizontal rod from position close to N-pose (reference pose), reaches the vertical target and goes to position to pick up next clothespin on horizontal rod or in case of last clothespin and last vertical target the movement ended when the hand almost reached reference pose, see **Figure 19**. The reference pose is shown on right side on **Figure 17**, the subjects in the measurements did not make perfect reference pose, therefore, for standardization it was decided to define the starting posture as posture similar to reference pose, meaning the reference pose was not perfect. The same applied to downward assessment, the range for one movement was defined as going from position close to reference pose to the vertical target, picking up the clothespin and placing it on a horizontal rod, the next movement would have the same starting time as ending time of previous movement. Plot was made to visualize the movements for each clothespin and each trial, to visualize all trials with normalized time at the same graph and to make sure that correct ranges for the movements have been detected. Additionally, the plot of mean movement of able-bodied subjects and plot of movement of not affected and affected side for amputees were made for each joint obtained in **Table 4**.

Next part of the analysis was to find the maximum angle for each movement. To begin with the dominant movement of downward and upward assessment was obtained, for each participant, trial and defined movement reaching three different targets. The detection of dominant movement was only done for trunk lateral bending, where the lateral bending of the trunk to the left side is positive and to the right side is negative. It was done to track the dominant movement reaching the vertical and horizontal target and to find its corresponding maximum angle. In detail, many cases of trunk lateral bending while reaching the vertical target included lateral bending to the right and left side, the detection of dominant movement was to solve the issue and to find the movement that subject was using often or for the longer time. The movement of shoulder adduction would only be negative form reference position towards internal rotation as seen on right figure of **Figure 8**. The extension of the elbow would only be negative if reaching extension from the reference pose, see left figure on **Figure 7**. Moreover, the mean of each maximum angle was calculated for each subject, trial and movement.

The comparison of the maximum angles of each movement was provided for all joints listed in **Table 4**, only main results will be plotted. The first comparison included the right and left hand of able-bodied subjects, where the mean of each trial was calculated for each hand. The next comparison included prostheses users, defined as affected subjects. Comparison of both hands was provided for each subject among comparison of prosthesis/affected side. Lastly, able-bodied subjects were compared to the affected subjects, the mean of able-bodied subjects was compared to the prosthetic side of affected subject for each hand. The delta (Δ) difference between right-left hand and difference between subjects were calculated for each target as well as the overall difference of the movement. Lastly, the highest maximum measured values were obtained for able-bodied and affected subjects. Additionally, the percentage of movement utilization was determined based on the highest achievable degree of motion.

5 Results

5.1 CPRT - Upward Assessment

5.1.1 Comparison of Left and Right Hand – Able-bodied Subjects

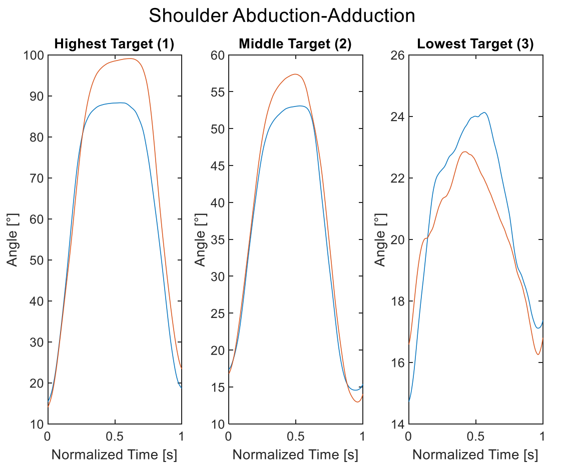

Figure 22 Mean shoulder abduction-adduction of right hand (red) and left hand (blue) during upwards assessment - Able-bodied subjects.

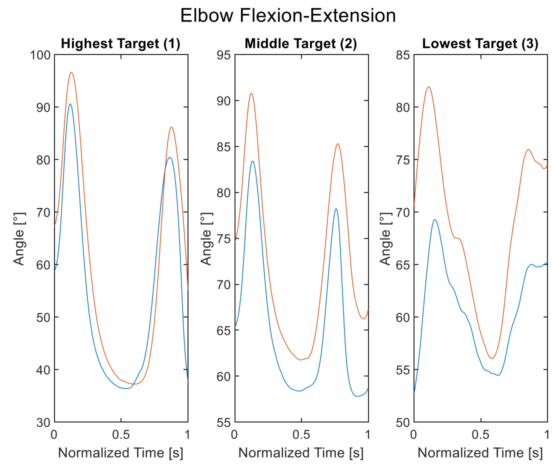

Figure 23 Mean elbow flexion-extension of right hand (red) and left hand (blue) during upwards assessment - Able-bodied subjects.

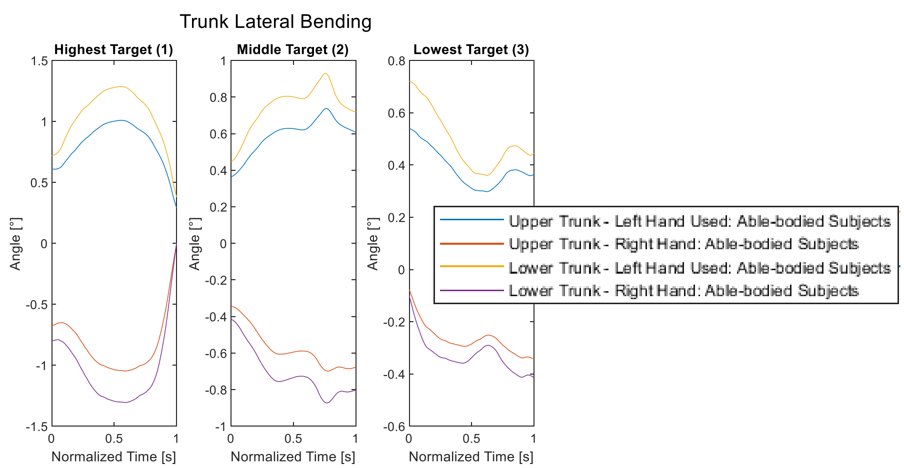

Figure 24 Mean upper and lower lateral trunk bending of right and left hand during upwards assessment – Able-bodied subjects.

Table 5 Comparison of left and right hand during upward assessment - Able-bodied subjects.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand [°]	Right Hand [°]	Δ Highest Target [°]	Left Hand [°]	Right Hand [°]	Δ Middle Target [°]	Left Hand [°]	Right Hand [°]	Δ Lowest Target [°]	Mean Difference Between Left and Right Hand [°]
Shoulder Abduction-Adduction	89.8	99.7	9.9	53.7	58	4.3	26.1	25.1	1	5.1
Elbow Flexion-Extension	104.6	108	3.4	88.2	96.2	8	81.7	90.6	8.9	6.8
Upper Trunk Lateral Bending	1.1	-1.2	2.3	0.8	-0.8	1.6	0.5	-0.4	0.9	1.6
Lower Trunk Lateral Bending	1.4	-1.4	2.8	1	-0.9	1.9	0.7	-0.5	1.2	2

5.1.2 Comparison of Left and Right Hand among Prosthetic Side – Affected Subjects

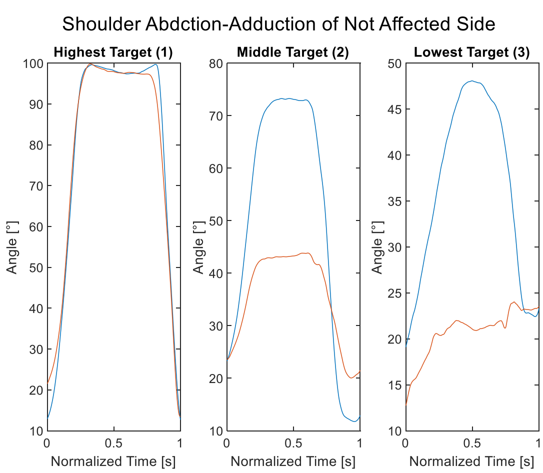

Figure 25 Shoulder abduction-adduction of not affected side during upwards assessment- P01 using left hand (blue) and P02 using right hand (red).

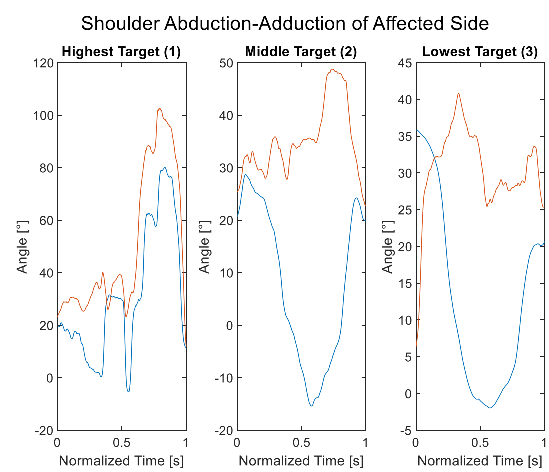

Figure 26 Shoulder abduction-adduction of affected side during upwards assessment- P01 using right hand (blue) and P02 using left hand (red).

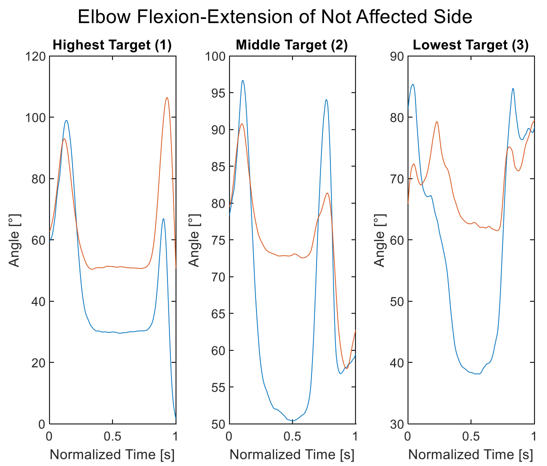

Figure 27 Elbow flexion-extension of not affected side during upwards assessment - P01 using left hand (blue) and P02 using right hand (red).

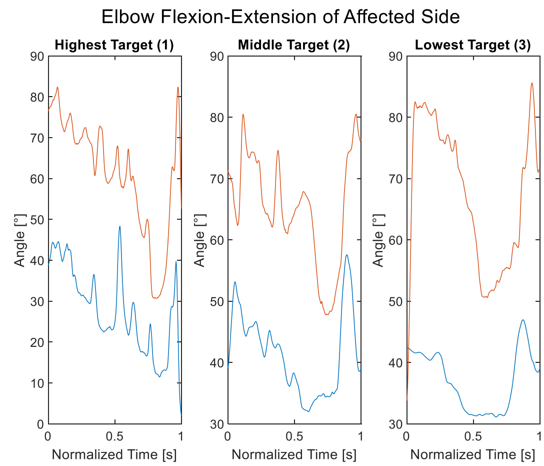

Figure 28 Elbow flexion-extension of affected side during upwards assessment - P01 using right and (blue) P02 using left hand (red).

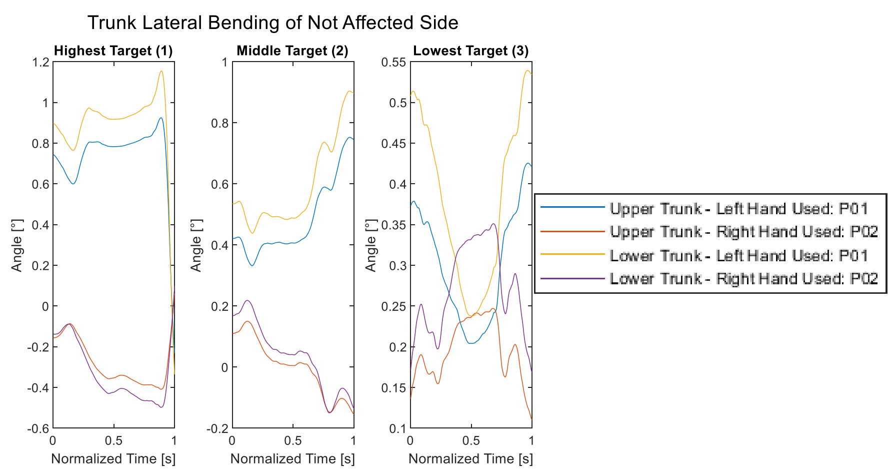

Figure 29 Trunk lateral bending of not affected side during upwards assessment.

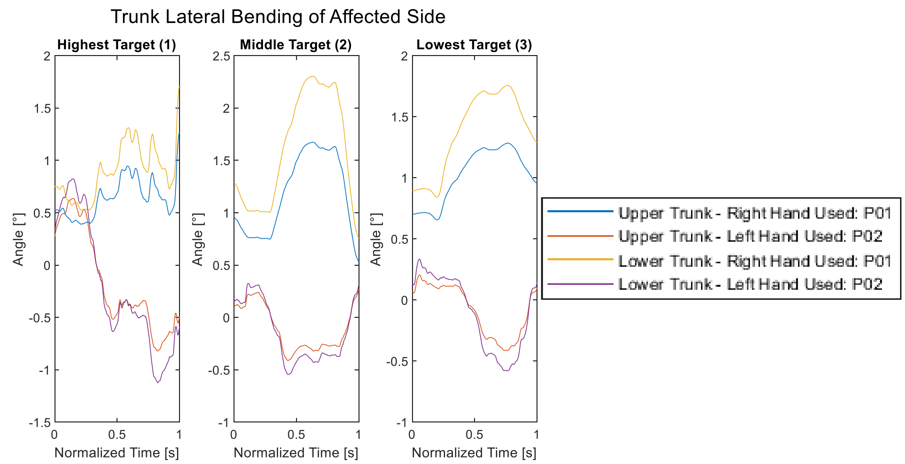

Figure 30 Trunk lateral bending of affected side during upwards assessment.

Table 6 Comparison of left and right hand during upward assessment - P01.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand [°]	Right Hand [°]	Δ Highest Target [°]	Left Hand [°]	Right Hand [°]	Δ Middle Target [°]	Left Hand [°]	Right Hand [°]	Δ Lowest Target [°]	Mean Difference Between Left and Right Hand [°]
Shoulder Abduction-Adduction	101.2	91.8	9.4	73.6	30.4	43.2	48.2	35.8	12.4	21.7
Elbow Flexion-Extension	103.3	61.4	41.9	106	65.1	40.9	93.2	54.2	39	40.6
Upper Trunk Lateral Bending	0.9	1.4	0.5	0.8	1.8	1	0.5	1.4	0.9	0.8
Lower Trunk Lateral Bending	1.2	1.9	0.7	0.9	2.5	1.6	0.7	1.9	1.2	1.2

Table 7 Comparison of left and right hand during upward assessment - P02.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand [°]	Right Hand [°]	Δ Highest Target [°]	Left Hand [°]	Right Hand [°]	Δ Middle Target [°]	Left Hand [°]	Right Hand [°]	Δ Lowest Target [°]	Mean Difference Between Left and Right Hand [°]
Shoulder Abduction-Adduction	103.5	100.3	3.2	50.1	44.2	5.9	44.5	24.3	20.2	9.8
Elbow Flexion-Extension	97.2	107.9	10.7	88.7	90.8	2.1	91	82.8	8.2	7
Upper Trunk Lateral Bending	-1.2	-0.4	0.8	-0.3	-0.1	0.2	0	0.3	0.3	0.4
Lower Trunk Lateral Bending	-1.5	-0.5	1	-0.3	-0.1	0.2	0	0.4	0.4	0.5

Table 8 Comparison of left and right hand during upward assessment - P02 using left hand and P01 right hand.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand P02 [°]	Right Hand P01 [°]	Δ Highest Target [°]	Left Hand P02 [°]	Right Hand P01 [°]	Δ Middle Target [°]	Left Hand P02 [°]	Right Hand P01 [°]	Δ Lowest Target [°]	Mean Difference Between Left and Right Hand [°]
Shoulder Abduction-Adduction	103.5	91.8	11.7	50.1	30.4	19.7	44.5	35.8	8.7	13.4
Elbow Flexion-Extension	97.2	61.4	35.8	88.7	65.1	23.6	91	54.2	36.8	32.1
Upper Trunk Lateral Bending	-1.2	1.4	2.6	-0.3	1.8	2.1	0	1.4	1.4	2
Lower Trunk Lateral Bending	-1.5	1.9	3.4	-0.3	2.5	2.8	0	1.9	1.9	2.7

5.1.3 Comparison of Left and Right Hand – Able-bodied and Affected Subjects

Table 9 Comparison of right hands during upward assessment - Able-bodied subjects and P01.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Right Hand: Able-bodied Subjects [°]	Right Hand: P01 [°]	Δ Highest Target [°]	Right Hand: Able-bodied Subjects [°]	Right Hand: P01 [°]	Δ Middle Target [°]	Right Hand: Able-bodied Subjects [°]	Right Hand: P01 [°]	Δ Lowest Target [°]	Mean Difference Between Able-bodied and P01 [°]
Shoulder Abduction-Adduction	99.7	91.8	7.9	58	30.4	27.6	25.1	35.8	10.7	15.4
Elbow Flexion-Extension	108	61.4	46.6	96.2	65.1	31.1	90.6	54.2	36.4	38
Upper Trunk Lateral Bending	-1.2	1.4	2.6	-0.8	1.8	2.6	-0.4	1.4	1.8	2.3
Lower Trunk Lateral Bending	-1.4	1.9	3.3	-0.9	2.8	3.4	-0.5	1.9	2.4	3

Table 10 Comparison of left hands during upward assessment - Able-bodied subjects and P02.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand: Able-bodied Subjects [°]	Left Hand: P02 [°]	Δ Highest Target [°]	Left Hand: Able-bodied Subjects [°]	Left Hand: P02 [°]	Δ Middle Target [°]	Left Hand: Able-bodied Subjects [°]	Left Hand: P02 [°]	Δ Lowest Target [°]	Mean Difference Between Able-bodied and P02[°]
Shoulder Abduction-Adduction	89.8	103.5	13.7	53.7	50.1	3.6	26.1	44.5	18.4	11.9
Elbow Flexion-Extension	104.6	97.2	7.4	88.2	88.7	0.5	81.7	91	9.3	5.7
Upper Trunk Lateral Bending	1.1	-1.2	2.3	0.8	-0.3	1.1	0.5	0	0.5	1.3
Lower Trunk Lateral Bending	1.4	-1.5	2.9	1	-0.3	1.3	0.7	0	0.7	1.6

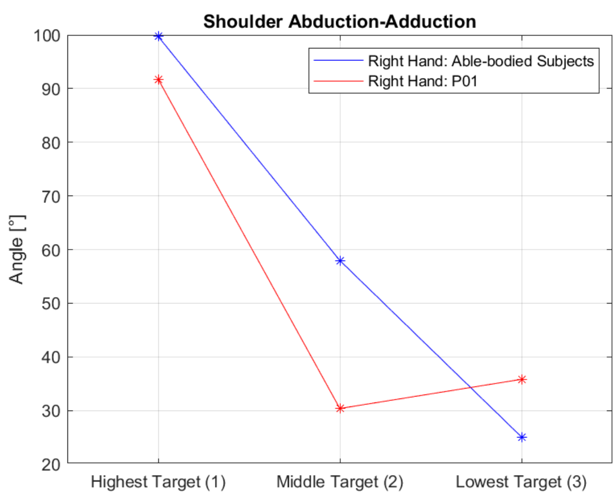

Figure 31 Comparison of right hands during upwards assessment: shoulder abduction-adduction – Able-bodied subjects and P01.

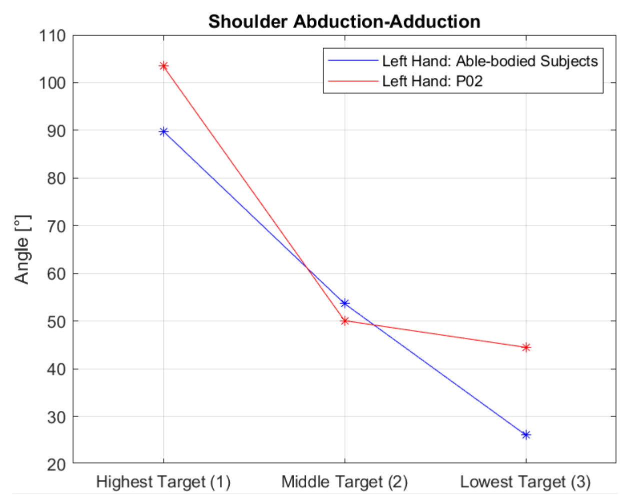

Figure 32 Comparison of left hands during upwards assessment: shoulder abduction-adduction – Able-bodied subjects and P02.

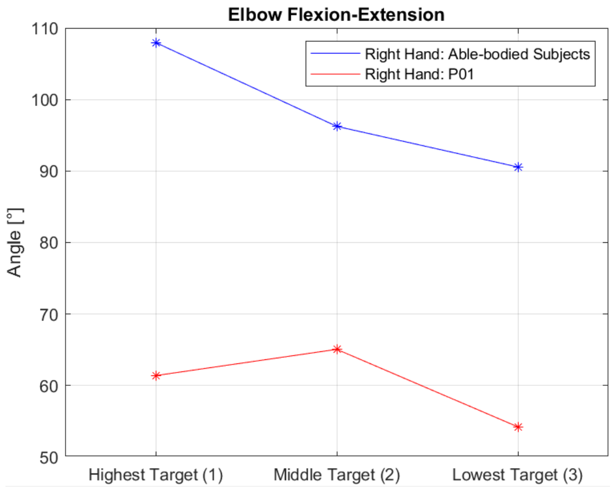

Figure 33 Comparison of right hands during upwards assessment: elbow flexion-extension - Able-bodied subjects and P01.

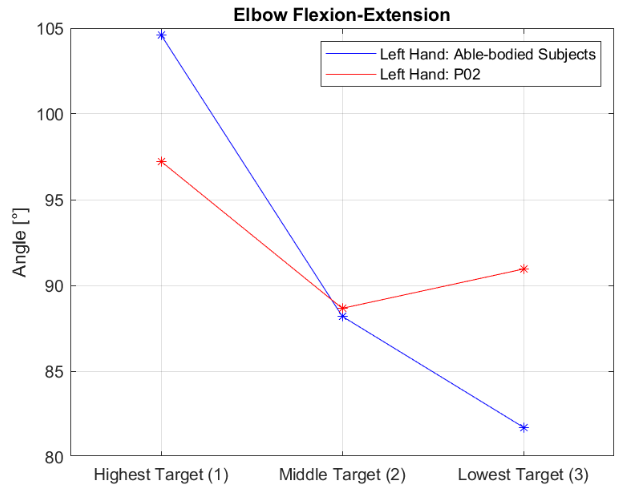

Figure 34 Comparison of left hands during upwards assessment: elbow flexion-extension - Able-bodied subjects and P02.

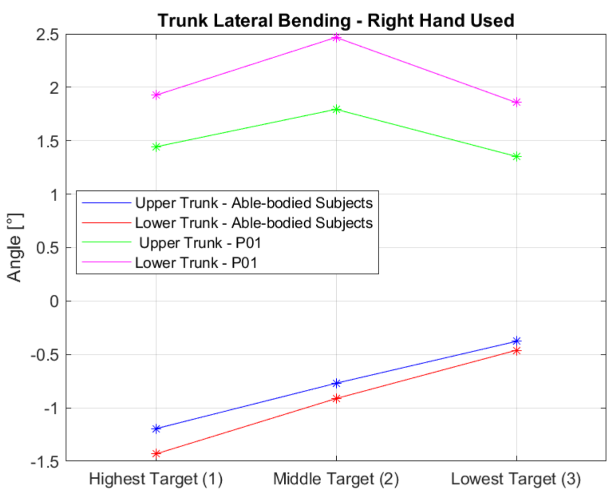

Figure 35 Comparison of upper and lower trunk lateral bending while using right hand during upward assessment – Able-bodied subjects and P01.

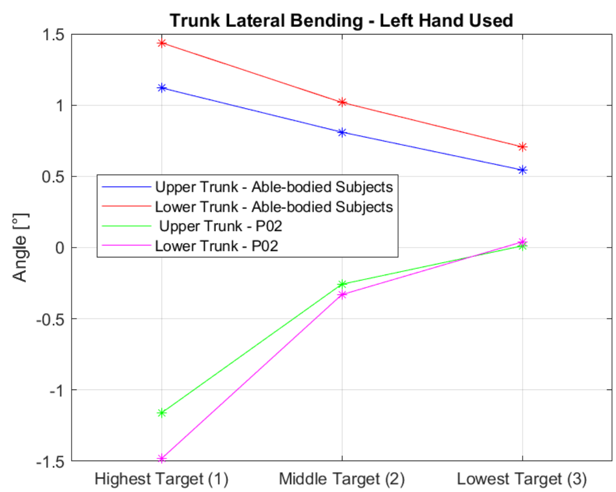

Figure 36 Comparison of upper and lower trunk lateral bending while using left hand during upward assessment – Able-bodied subjects and P02.

5.2 CPRT - Downward Assessment

5.2.1 Comparison of Left and Right Hand – Able-bodied Subjects

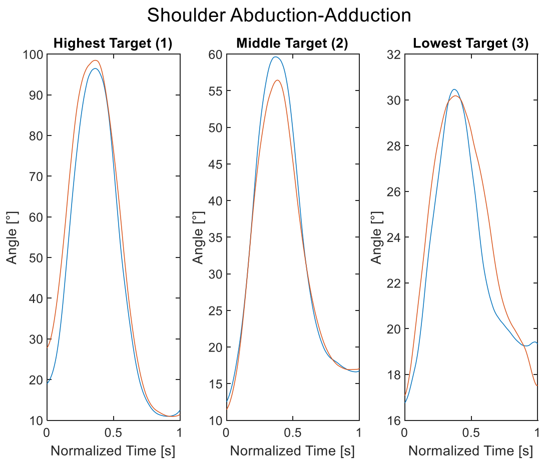

Figure 37 Mean shoulder abduction-adduction of right hand (red) and left hand (blue) during downwards assessment - Able-bodied subjects.

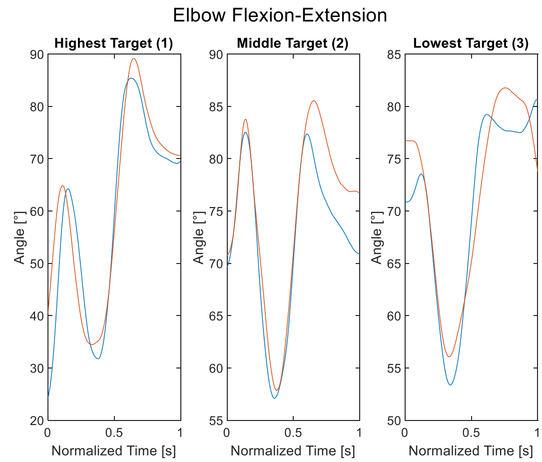

Figure 38 Mean elbow flexion-extension of right hand (red) and left hand (blue) during downwards assessment - Able-bodied subjects.

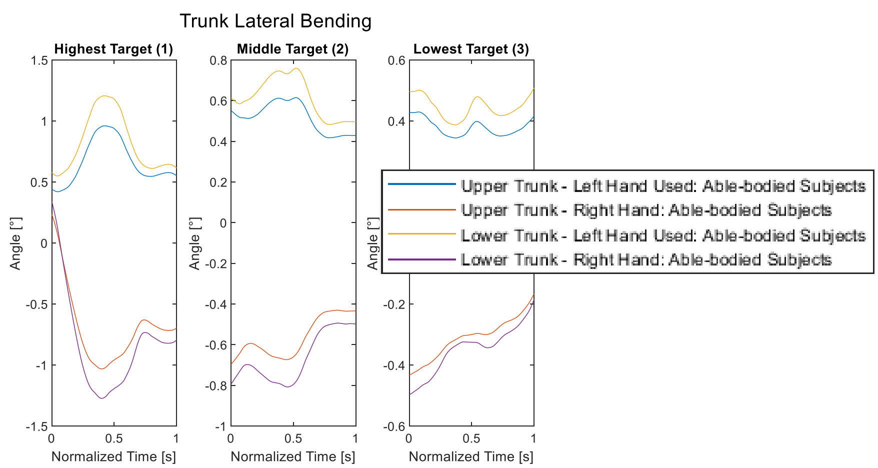

Figure 39 Mean upper and lower lateral trunk bending of right and left hand during downwards assessment – Able-bodied subjects.

Table 11 Comparison of left and right hand during downward assessment - Able-bodied subjects.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand [°]	Right Hand [°]	∆ Highest Target [°]	Left Hand [°]	Right Hand [°]	∆ Middle Target [°]	Left Hand [°]	Right Hand [°]	∆ Lowest Target [°]	Mean Difference Between Left and Right Hand [°]
Shoulder Abduction-Adduction	99.5	103.6	4.1	62	58.6	3.4	33.3	32	1.3	2.9
Elbow Flexion-Extension	100.3	99	1.3	93.7	94.3	0.5	87.3	86.5	0.8	0.9
Upper Trunk Lateral Bending	1.2	-1.2	2.4	0.8	-0.9	1.7	0.5	-0.5	1	1.7
Lower Trunk Lateral Bending	1.5	-1.4	2.9	0.9	-1	1.9	0.7	-0.5	1.2	2

5.2.2 Comparison of Left and Right Hand – Affected Subjects

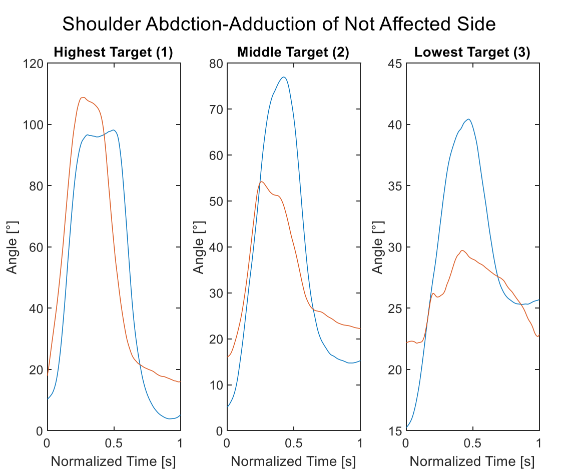

Figure 40 Shoulder abduction-adduction of not affected side during downwards assessment- P01 using left hand (blue) and P02 using right hand (red).

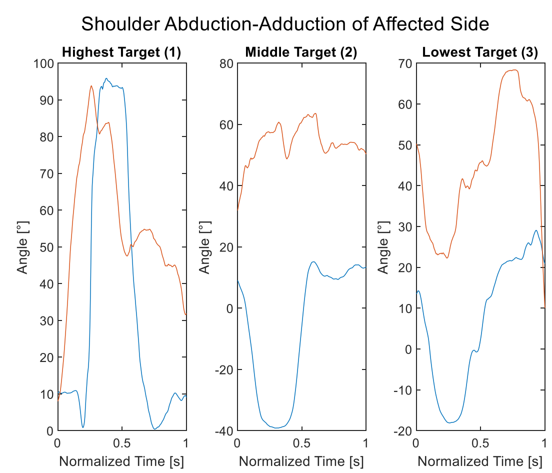

Figure 41 Shoulder abduction-adduction of affected side during downwards assessment- P01 using left hand (blue) and P02 using right hand (red).

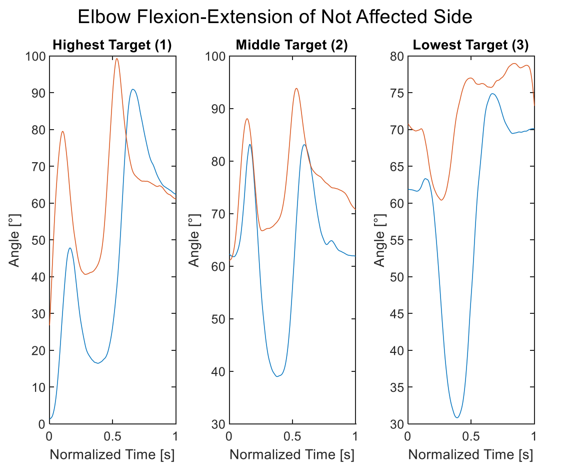

Figure 42 Elbow flexion-extension of not affected side during downwards assessment- P01 using left hand (blue) and P02 using right hand (red).

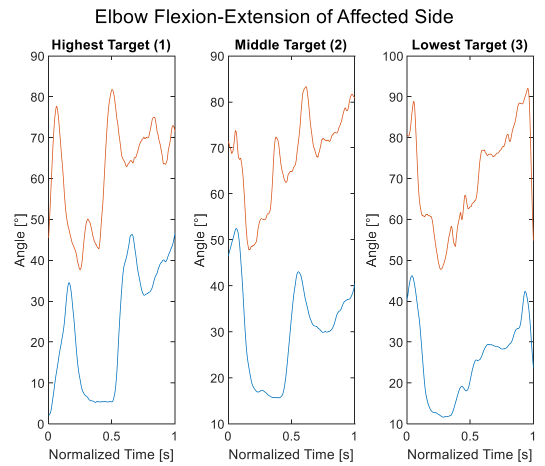

Figure 43 Elbow flexion-extension of affected side during downwards assessment- P01 using left hand (blue) and P02 using right hand (red).

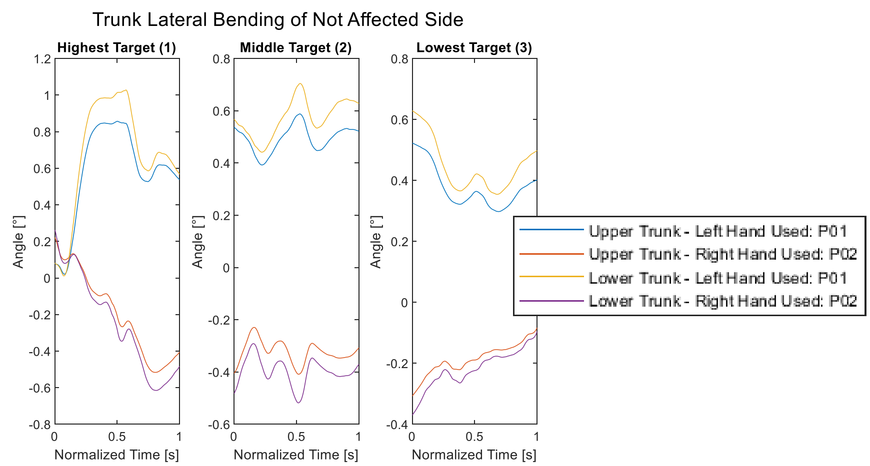

Figure 44 Trunk lateral bending of not affected side during downwards assessment.

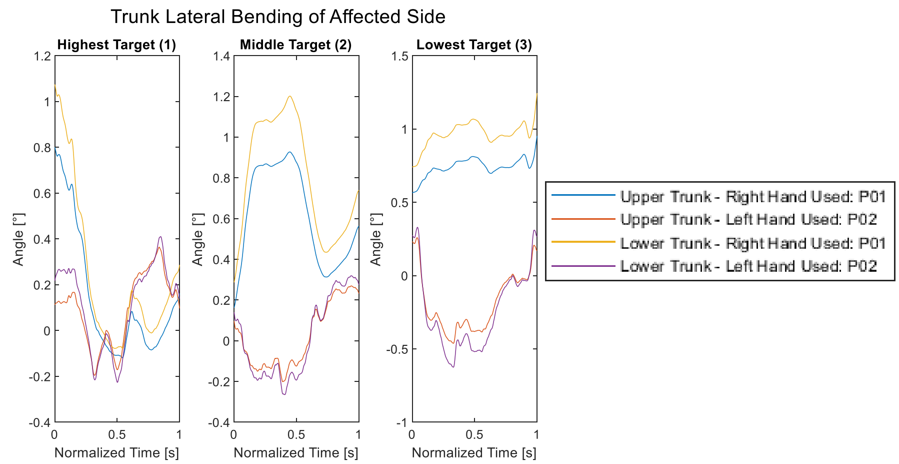

Figure 45 Trunk lateral bending of affected side during downwards assessment.

Table 12 Comparison of left and right hand during downward assessment - P01.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand [°]	Right Hand [°]	Δ Highest Target [°]	Left Hand [°]	Right Hand [°]	Δ Middle Target [°]	Left Hand [°]	Right Hand [°]	Δ Lowest Target [°]	Mean Difference Between Left and Right Hand [°]
Shoulder Abduction-Adduction	98.5	98.6	0.1	77.2	17.9	59.3	40.5	31.2	9.3	22.9
Elbow Flexion-Extension	98.4	61	37.4	90	61.5	28.5	80.1	55.3	24.8	30.2
Upper Trunk Lateral Bending	0.9	0.5	0.4	0.6	1	0.5	0.5	1	0.5	0.4
Lower Trunk Lateral Bending	1	0.7	0.3	0.7	1.2	0.6	0.6	1.3	0.7	0.5

Table 13 Comparison of left and right hand during downward assessment - P02.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand [°]	Right Hand [°]	∆ Highest Target [°]	Left Hand [°]	Right Hand [°]	∆ Middle Target [°]	Left Hand [°]	Right Hand [°]	∆ Lowest Target [°]	Mean Difference Between Left and Right Hand [°]
Shoulder Abduction-Adduction	106.3	109.1	2.8	70.3	55.5	14.8	72.2	30.3	41.9	19.8
Elbow Flexion-Extension	89.7	102.3	12.6	92.5	95.9	3.4	92.9	87	5.9	7.3
Upper Trunk Lateral Bending	-0.1	-0.5	0.6	0.1	-0.5	0.6	-0.5	-0.3	0.2	0.5
Lower Trunk Lateral Bending	-0.2	-0.6	0.8	0	-0.6	0.6	-0.7	-0.4	0.3	0.6

Table 14 Comparison of left and right hand during downward assessment - P02 using left hand and P01 right hand.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand P02 [°]	Right Hand P01 [°]	∆ Highest Target [°]	Left Hand P02 [°]	Right Hand P01[°]	∆ Middle Target [°]	Left Hand P02 [°]	Right Hand P01 [°]	∆ Lowest Target [°]	Mean Difference Between Left and Right Hand [°]
Shoulder Abduction-Adduction	106.3	98.6	7.7	70.3	17.9	52.4	72.2	31.2	41	33.7
Elbow Flexion-Extension	89.7	61	28.7	92.5	61.5	31	92.9	55.3	37.6	32.4
Upper Trunk Lateral Bending	-0.1	0.5	0.4	0.1	1	0.9	-0.5	1	1.5	0.9
Lower Trunk Lateral Bending	-0.2	0.7	0.5	0	1.2	1.2	-0.7	1.3	2	1.2

5.2.3 Comparison of Left and Right Hand – Able-bodied and Affected Subjects

Table 15 Comparison of right hands during downward assessment - Able-bodied subjects and P01.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Right Hand: Able-bodied Subjects [°]	Right Hand: P01 [°]	Δ Highest Target [°]	Right Hand: Able-bodied Subjects [°]	Right Hand: P01 [°]	Δ Middle Target [°]	Right Hand: Able-bodied Subjects [°]	Right Hand: P01 [°]	Δ Lowest Target [°]	Mean Difference Between Able-bodied and P01 [°]
Shoulder Abduction-Adduction	103.6	98.6	5	58.6	17.9	40.7	32	31.2	0.8	15.5
Elbow Flexion-Extension	99	61	38	94.3	61.5	32.8	86.5	55.3	31.2	34
Upper Trunk Lateral Bending	-1.2	0.5	1.7	-0.9	0.9	1.9	-0.5	1	1.5	1.7
Lower Trunk Lateral Bending	-1.4	0.7	2.1	-1	1.2	2.2	-0.5	1.3	1.8	2

Table 16 Comparison of left hands during downward assessment - Able-bodied subjects and P02.

	Highest Target			Middle Target			Lowest Target			
Type of Movement	Left Hand: Able-bodied Subjects [°]	Left Hand: P02 [°]	Δ Highest Target [°]	Left Hand: Able-bodied Subjects [°]	Left Hand: P02 [°]	Δ Middle Target [°]	Left Hand: Able-bodied Subjects [°]	Left Hand: P02 [°]	Δ Lowest Target [°]	Mean Difference Between Able-bodied and P02 [°]
Shoulder Abduction-Adduction	99.5	106.3	6.8	62	70.3	8.3	33.3	72.2	38.9	18
Elbow Flexion-Extension	100.3	89.7	10.6	93.7	92.5	1.2	87.3	92.9	5.6	5.8
Upper Trunk Lateral Bending	1.2	0.1	1.1	0.8	0.1	0.7	0.5	-0.5	1	0.9
Lower Trunk Lateral Bending	1.5	0.2	1.3	0.9	0	0.9	0.7	-0.7	1.4	1.2

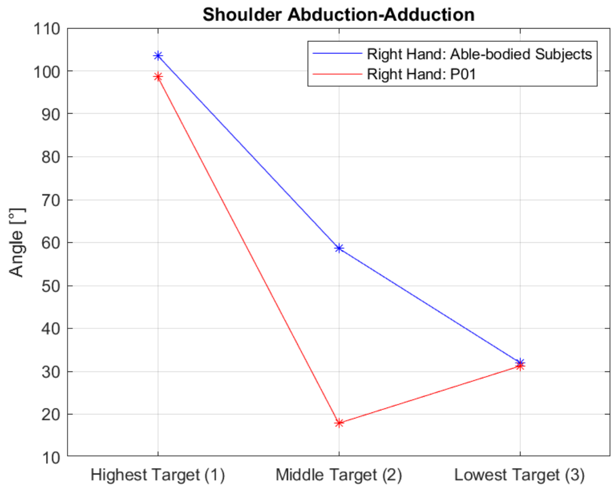

Figure 46 Comparison of right hands during downward assessment: shoulder abduction-adduction – Able-bodied subjects and P01.

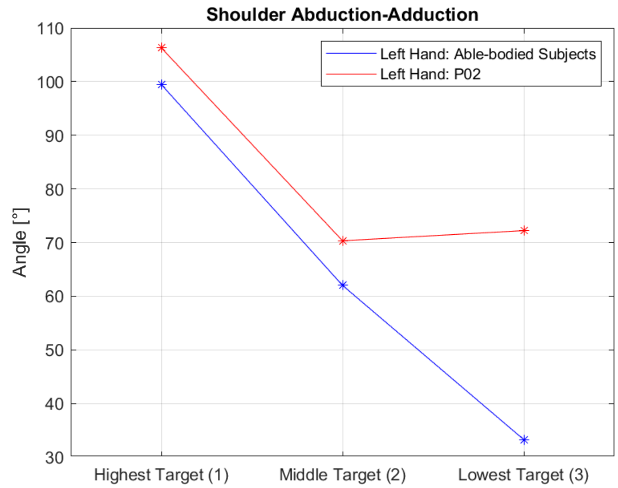

Figure 47 Comparison of left hands during downward assessment: shoulder abduction-adduction – Able-bodied subjects and P02.

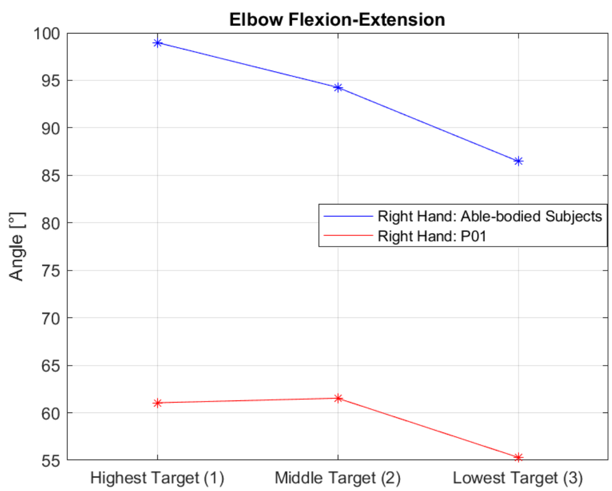

Figure 48 Comparison of right hands during downward assessment: elbow flexion-extension – Able-bodied subjects and P01.

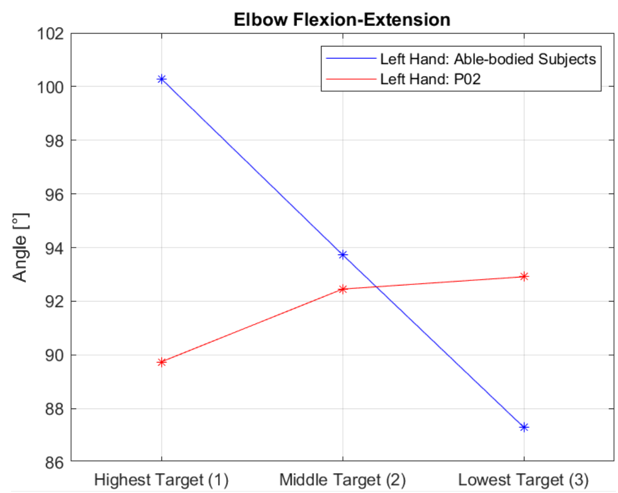

Figure 49 Comparison of left hands during downward assessment: elbow flexion-extension – Able-bodied subjects and P01.

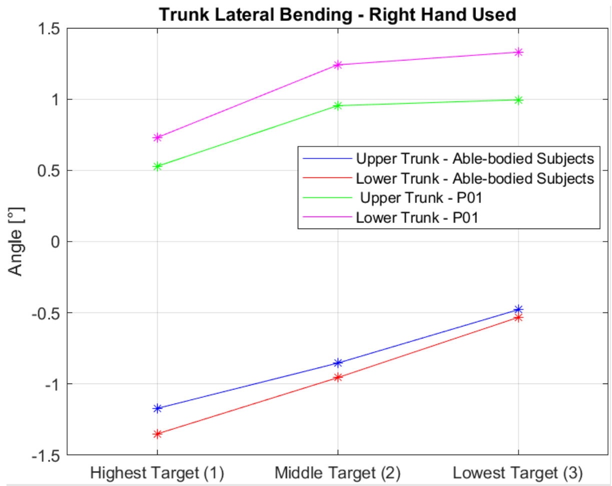

Figure 50 Comparison of upper and lower trunk lateral bending while using right hand during downward assessment – Able-bodied subjects and P01.

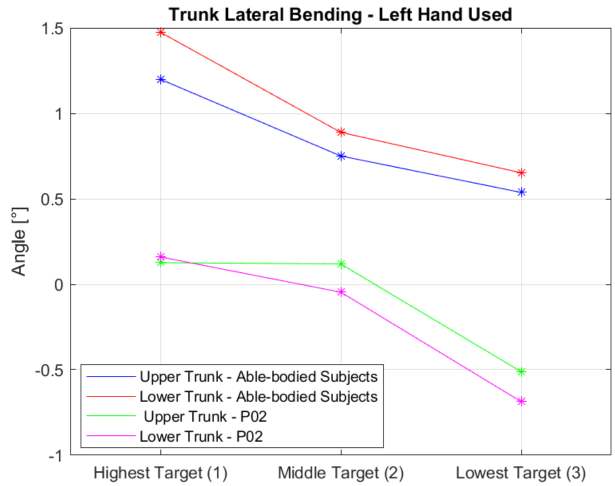

Figure 51 Comparison of upper and lower trunk lateral bending while using left hand during downward assessment – Able-bodied subjects and P01.

6 Discussion

The goal of the study was to compare and observe the upper limb movements of able-bodied subjects and transradial prosthesis users during CPRT.

Table 17 Highest measured value (MV) and standard deviation (STD) for upward assessment compared to maximum degree of movement among calculated percentage (%) of usage.

Movement	Degrees	Able-bodied Subjects						Affected Subjects					
		Highest Target		Middle Target		Lowest Target		Highest Target		Middle Target		Lowest Target	
		MV±STD	%	MV±STD	%	MV±STD	%	MV±STD	%	MV±STD	%	MV±STD	%
Shoulder Abduction	180°	99.7° ± 13.3	55.4	58° ± 10.6	32.2	26.1° ± 6.1	14.5	103.5° ± 27.7	57.5	50.1° ± 6.8	27.8	44.5° ± 5.8	24.7
Elbow Flexion	145°	108° ± 10.5	74.5	96.2° ± 11	66.3	90.6° ± 11.1	62.5	97.2° ± 14	67	58.7° ± 8.8	40.5	54.2° ± 11.9	37.4
Upper Trunk Lateral Bending	40°	-1.2° ± 0.5	3	0.8° ± 0.3	2	0.5° ± 0.3	1.2	1.4° ± 0.2	3.5	1.8° ± 0.4	4.5	1.4° ± 0.2	3.5
Lower Trunk Lateral Bending	20°	1.4° ± 0.6	7	1° ± 0.3	5	0.7° ± 0.4	3.5	1.9° ± 0.2	9.5	2.5° ± 0.5	12.5	1.9° ± 0.3	9.5

Table 18 Highest measured value (MV) and standard deviation (STD) for downward assessment compared to maximum degree of movement among calculated percentage (%) of usage.

Movement	Degrees	Able-bodied Subjects						Affected Subjects					
		Highest Target		Middle Target		Lowest Target		Highest Target		Middle Target		Lowest Target	
		MV±STD	%	MV±STD	%	MV±STD	%	MV±STD	%	MV±STD	%	MV±STD	%
Shoulder Abduction	180°	103.6° ± 16.1	57.5	62° ± 14.4	34.4	33.3° ± 5.7	18.5	106.3° ± 19.8	59	70.3° ± 5.8	39	72.2° ± 15.6	40.1
Elbow Flexion	145°	100.3° ± 13.7	69.2	94.3° ± 13.3	65	87.3° ± 15.1	60.2	89.7° ± 12.2	61.9	92.5° ± 9.5	63.8	92.9° ± 12.3	64.1
Upper Trunk Lateral Bending	40°	1.2° ± 0.4	3	-0.9° ± 0.3	2.2	0.5° ± 0.2	1.2	0.5° ± 0.3	1.2	1° ± 0.2	2.5	1° ± 0.1	2.5
Lower Trunk Lateral Bending	20°	1.5° ± 0.5	7.5	-1° ± 0.4	5	0.7° ± 0.2	3.5	0.7° ± 0.3	3.5	1.5° ± 0.3	7.5	1.3° ± 0.1	6.5

The comparison of the right and left hand of able-bodied subjects showed that right and left hand are symmetrical for both upwards and downwards assessment for all joints and movements in the analysis. The greatest differences for both assessments and between right and left hand were observed for the elbow flexion-extension with the mean difference of 6.8°, see **Table 5** and **Table 11**, for additional visualization Appendix 9.1 and 9.3. Additionally, it was observed while subjects were using the right hand for the assessment the upper and lower trunk bended mainly to the negative side resulting bending to the right side, meaning that trunk bended into same direction as the hand that was used for the assessment. For the left hand the results showed the opposite, the trunk bended to the left side resulting positive lateral bending of the trunk, see **Figure 52** [15], **Figure 62** and **Figure 76** for visualization of the results.

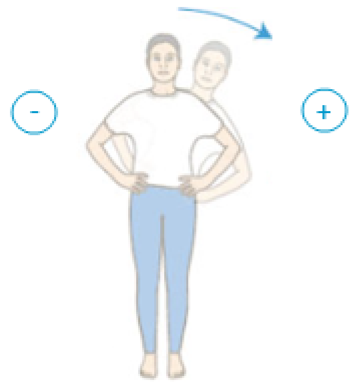

Figure 52 Directions of lateral trunk bending. Bending to the left side: positive (+) movement and bending to the right side: negative (-) movement.

The comparison of right and left hand of P01 right prosthesis user showed greater differences between the hands and the results showed that they were not symmetrical as able bodied subjects, see Appendix 9.2 for upward assessment and 9.4 for downward assessment. For the upwards assessment the mean differences between the hands of the shoulder abduction-adduction resulted in 21.7°, of the elbow flexion-extension in 40.6°, of the upper trunk lateral bending in 0.8° and of the lower trunk in 1.2°, see **Table 6**. For the downwards assessment the mean differences between the hands of the shoulder abduction-adduction was 22.9°, of the elbow flexion-extension was 30.2°, of the upper trunk lateral bending was 0.4° and of the lower trunk was 0.5°, see **Table 12**. The greatest difference was observed for elbow flexion-extension for upward assessment.

The results of P02 were more symmetrical while comparing the right and left hand than of P01. However, they were not as symmetrical as the right and left hands of able-bodied subjects, see Appendix 9.2 and 9.4. For the upward assessment the mean difference of the shoulder abduction-adduction was 9.8°, for the elbow flexion-extension was 7°, for the upper trunk lateral bending was 0.4° and for the lower trunk it was 0.5°, see **Table 8**. For the downward assessment the mean difference of the shoulder abduction-adduction was 19.8°, the elbow flexion-extension was 7.3°, the upper trunk lateral bending was 0.5° and lower trunk was 0.6°, see **Table 13**. Therefore, the greatest difference was obtained for shoulder abduction-adduction for downward assessment.

The comparison of the affected sides of P01 and P02 showed greatest difference for shoulder abduction-adduction for downward assessment, the difference was 33.7°, see **Table 8** for upward assessment and **Table 14** for downward assessment.

The comparison of able-bodied subjects using right hand and P01 right prosthesis user showed similar results for both assessments. For both assessments the greatest difference was observed for elbow flexion-extension, for upwards assessment the mean difference was 38° and for downwards assessment it was 34°. The main difference between the able-bodied subjects and P01 was observed for trunk lateral bending. The lateral trunk bending while using affected hand, in this case the right hand, bended mainly to the negative direction. Meaning that P01 was bending the trunk to opposite direction as able-bodied subjects for both assessments, see **Figure 35** for upwards assessment and **Figure 50** for downward assessment.

It is important to mention that the maximum angle of all elbow flexions-extensions occurred while picking up the clothespin on horizontal rod or while going to the position to pick up the next one.

The greatest differences while comparing left hand of able-bodied subjects and P02 left prosthesis user were observed for shoulder abduction-adduction for both assessments. For upward assessment the mean difference was 11.9° and for downwards assessment it was 18°. The same movement behavior was observed in the comparison of able-bodied subjects using left hand and P02 left prosthesis user for trunk lateral bending as in the comparison of able-bodied subjects using right hand and P01 right prosthesis user. The P02 was performing the opposite movement of trunk lateral bending compared to able-bodied subjects, see **Figure 36** and **Figure 51**.

Looking into the strategy of movement to complete the task that was chosen by able bodied subjects during upwards and downwards assessments, it is visible that the mean movement of all subjects showed shoulder abduction to reach the targets on vertical rod, see **Figure 22** and **Figure 37**. However, comparing every subjects and plotting them on the same graph it is visible that all subjects used more less the same strategies to complete the tasks to reach highest and middle targets on vertical rod, but the strategies to reach the lowest target on vertical rod showed wider range of strategies of choice, see Appendix 9.1 and 9.3.

The strategies used by able-bodied subject while looking into mean movement of the elbow during both assessments showed that subjects used flexion to pick up the clothespin on horizontal rod, went to extension to place the clothespin on vertical rod and went back to flexion to pick up the next clothespin, see **Figure 23** and **Figure 38**. Looking at each subject separately it is visible that the strategies are similar however, greater strategies differences are visible than for the shoulder, see Appendix 9.1 and 9.3.

The mean strategy of movement chosen by able-bodied subjects of the trunk lateral bending is to be seen on **Figure 24** and **Figure 39**. Like mentioned before, able-bodied subjects bended their trunk to the same side as the hand that was used for the assessment, resulting negative trunk bending while using right hand and positive trunk bending while using left hand to complete the task. All subjects used similar strategies to complete both assessments, see Appendix 9.1 and 9.3.

The strategy chosen by affected subjects of not affected side showed similar movement as strategy chosen by able-bodied subjects for the shoulder and both assessments, see **Figure 25** and **Figure 40**. Looking into strategy of affected side for upward assessment, it is visible that P01 uses complete shoulder adduction to reach all targets, where the mean angle < 0° in the middle of the graph, see **Figure 26**. Therefore, P01 goes from reference position into complete adduction as shown on the right side on **Figure 8**. While P02 uses mainly shoulder abduction to complete the same assessment. It is visible that P02 differs from able-bodied subjects in way that the movement is not as clear, the ROM is changing rapidly. It is seen that subject P02 does switches between shoulder abduction-adduction to complete the task, however, the subject uses shoulder abduction to reach the vertical target. For the downward assessment similar results were obtained. However, P01 uses shoulder abduction to reach the highest target on vertical rod, and shoulder adduction for other targets as described before while using affected side. Moreover, P01 and P02 used similar strategies for downward assessment, P02 used less of shoulder abduction as for upwards assessment to reach the middle and lowest targets on vertical rod, see **Figure 41**.

Looking into the movement of the elbow of affected subjects and not affected side it is visible that the strategy is similar to the strategy used by able-bodied subjects for both assessments, see **Figure 27** and **Figure 42**. Moreover, the affected side show similar results for both assessments. The main difference is that the movement is not as smooth as using not affected side estimated visually, it is clearly visible on **Figure 28** and **Figure 43**. The ideal movement for the elbow flexion-extension would look like on **Figure 23** and **Figure 38**, where individual does not have difficulties completing the assessment, therefore, the movement is smooth and does not have any disturbances like seen on the graph.

The strategy of trunk lateral bending used by affected subjects differences from the strategy of able-bodied subjects for both assessments while using affected side. Affected subjects while using affected side seem to bend to the positive and negative sides, it is especially visible for P02, see **Figure 30** and **Figure 45**. The maximum angle for the trunk lateral bending was calculated for the dominant movement described in chapter 4.4. Therefore, if the participant was using more of the negative lateral trunk bending it was defined as dominant movement or strategy to complete the assessment. Like mentioned before, the results of maximum angles for trunk lateral bending showed opposite results for able-bodied subjects and affected subjects.

It has been suggested that upper limb prostheses users make compensatory movements with both arms, affected and unaffected and their trunk to perform daily tasks. [19] [18] The visualization results of shoulder abduction-adduction and elbow flexion-extension of current study did not show any clues that affected participants make compensatory movements with not affected side while performing the assessments. However, the differences were seen in the trunk lateral bending while looking into comparison of able-bodied and affected subjects. The trunk lateral bending was the inverse of able-bodied subjects, meaning that affected subjects had opposite compensations compared to able-bodied subjects. Therefore, it is suggested that affected subjects made compensation movements with their trunk while bending laterally to complete the assessment.

Touillet et al[22] investigated BBT among transradial amputees fitted with hooks. In the study amputees used mainly shoulder abduction as compensatory movement during BBT, however, it is a different task than in current study. [22] The results in current study showed that P02 used mainly shoulder abduction to perform the tasks. Additionally, P02 had higher shoulder abduction angles reaching all vertical clothespins during downward assessment than able-bodied subjects. However, in some cases P02 used a combination of shoulder abduction-adduction to compete the tasks. On the other hand, P01 used mainly shoulder adduction to reach vertical targets and had mostly lower shoulder abduction movement compared to able-bodied subjects. It is important to mention that the maximum angles were only calculated and obtained for the maximum movement to complete the task. Meaning, maximum shoulder abduction, elbow flexion and lateral trunk bending.

Study by Hussaini et al[21] investigated able-bodied subjects and prosthesis users while performing a set of bimanual activities. The objective of the study was to identify and define compensation mechanisms for upper limb prosthesis users. The compensatory types were divided into three different categories; different postures that involves the adoption of new static posture to perform tasks compared to able-bodied subjects, ROM where the change of rotation is visible compared to able-bodied subjects and prepositioning that includes prepositioning the items in the workplace before the task, for more details see Chapter 3.4. The only applicable definition for current study is the ROM and the prepositioning. The ROM and change of rotation were visible for both P01 and P02 compared to able-bodied subjects. In few cases totally different strategies of movements were chosen by affected subjects compared to the able-bodied subjects, especially for shoulder abduction-adduction, see mean movement of able-bodied subjects on **Figure 22** and **Figure 37** and movement of affected subjects **Figure 26** and **Figure 41**. Additionally, the maximum movement of the trunk lateral bending of affected subjects showed opposite results compared to able-bodied subjects. Moreover, looking into the strategy chosen by affected subjects while using affected side in Xsens recordings it was visible that subject P01 favors lateral bend of the trunk to composite for wrist movement while P02 favors prepositioning of the clothespin, either at the start or end of the movement. The results suggest that affected subjects showed compensation movements in the shoulder and the trunk.

Valevivius et al[26] suggested that increased skill level reduces compensatory movements in the trunk. [26] Both prostheses users in the current study had experience with the prostheses for more than 2 years. However, P01 uses the prosthetic hand for 4-6h and P02 for 8-13h per day, resulting P02 being more experienced with the device. Moreover, the shorted daily wearing time of subject P01 could be because of possible pain that prosthetic hand is costing. Overall, P02 differenced less from able-bodied subjects than P01 which can be associated with experience level with the device. Additionally, subject P01 had congenital amputation while subject P02 had traumatic amputation. Therefore, subject P01 could have more difficulties with the control of the prosthetic hand. The subjects did differ in the limb length as well, subject P02 had longer residual limb length than subject P01. Lastly, the subjects had their amputation of opposite sides, which makes the comparison more challenging. Overall, those factors may have an impact on the comparison between the subjects.

Lastly, **Table 17** and **Table 18** display the highest maximum measured values for both assessment and reference values of the movement, respectively. Additionally, these tables indicate the percentage of the maximum degrees of the movement that was utilized. As the percentage increases, the risk of muscle stress also increases. In other words, a higher percentage indicates a greater likelihood or potential severity of muscle-related risks due to stress.

Controlling the upper limb prosthesis by myoelectric signal requires a lot of training and experience. Due to the lack of wrist control, prostheses users can develop different movement strategies, where some of them might result in compensatory movements. [23] [24]

Understanding the issues of current prosthesis and the movements of the prostheses users is a step-in to direction of improvement of quality of life of prostheses users, which is primary objective for Össur. Moreover, the results are intended to improve understanding of movement in limb-absent individuals and influence the development of prostheses and associated control methods. The understanding of those factors would help clinicians to improve the rehabilitation and training process.

Like mentioned before, around 50% of upper limb amputees develop problems in the intact limb due to prosthesis use, problems such as MSC and repetitive strain injury (RIS). [20] [21] Össur and the entire industry of the upper limb prosthetics are interested in how to avoid, predict and limit those problems. Additionally, the health care systems reimburse a device based on the effectiveness of the product, meaning that providing the product is beneficial for health of the patient. Lastly, the design of the upper limb prostheses should be closer to physiological hand. The results of current study suggest that the design of current prosthesis should be closer to physiological hand. The pronation-supination of the wrist is one of the most important movements of the body, it is indispensable for control of the orientation of the hand which allows the hand to assume the best position for grasping an object. The pronation-supination is the key movement for self-feeding and plays a major role in all actions of the hand, especially doing work. Current design has a lack of pronation-supination which might be responsible for the compensatory movement made by the prosthesis users. The compensatory movements made by affected subjects could be visible because of the limited wrist rotation or the feeling that subject might experience that the prosthetic hand is longer than not affected hand, which might result in opposite trunk lateral bending compared to able-bodied subjects.

From the study by Hussaini et al[21] it is possible to make a statement that the range of motion and the posture can be associated with musculoskeletal risks. The prepositioning would be intended to reduce that risk, due to limited DoF of the wrist. Those factors are important for the prosthesis training/therapy. Therefore, the rehabilitation process should ensure that patients get appropriate training with the device and patients should be monitored through the training process. Additionally, the results of the study suggest that amount of time of daily usage of the device can be associated with higher experience level and reduction of compensatory movements of the affected side.

Another factor to consider is from the psychological perspective. The confidence during the assessment could have a significant impact on the result. Where subject performing the assessment that had confidence would most likely have less difficulties completing the assessment.

Lastly, the study included out of able-bodied participants six right handed and three left handed subjects and both of the affected subjects marked their dominant hand as right, which might have an impact on the current results and the comparison.

For the future study design, it would be applicable to consider different analysis. The current study investigated detection of maximum range of motion of the movement of the shoulder, the elbow and the trunk. The maximum shoulder abduction-adduction movement of the able-bodied subjects occurred while the subjects were reaching the vertical rod, and all subjects used shoulder abduction to complete the tasks. However, for affected subjects it was depended on the strategy that was chosen. It would be more applicable to look at all strategies used by affected subjects and determine the maximum or minimum movement, applicable to the strategy of choice. Example of that would be P01 reaching the middle and lowest targets on **Figure 41**. The maximum angle for both cases occurs while P01 is picking up next clothespin on the horizontal rod. Therefore, in that case the minimum angle should be detected because P01 used shoulder adduction to reach the vertical target. This results that the maximum angle of the movement does not occur while performing the same movement and makes the comparison more challenging. The same applies to elbow flexion-extension. The maximum movement was detected while the subjects were picking up the clothespin on the vertical rod, resulting in maximum flexion. Therefore, it would be suggested to consider dividing the task into two different assessments, when the subjects are picking up the clothespin from horizontal rod and when subjects are reaching the vertical rod. It would result in clearer results and the comparison would make more sense. Moreover, the maximum angles of the movements of not affected hand of affected subjects should be compared to hand of interest in able-bodied population. In this study it could only be obtained by visualizing the strategy chosen to complete the assessment on a graph.

6.1 Limitations

The current study has multiple limitations. The main limitation of the study is the limited sample size, where only two transradial amputees participated. Additionally, the amputees had opposite affected side and different limb lenght. It is challenging to obtain subjects for such study that fulfills all the criteria (transradial amputee, same amputation side, same limb length, iLimb user, etc.). In this study the able-bodied subjects were compared to only one subject, meaning comparison of affected side of either P01 or P02 and corresponding hand of able-bodied subjects.

7 Conclusion

The study investigated comparison of able-bodied subjects and transradial prosthesis users during CPRT. The comparison of maximum movement of right and left hand of able-bodied subjects showed symmetrical results for the shoulder abduction-adduction, elbow flexion-extension and the trunk lateral bending during upwards and downwards assessments. While the comparison of maximum movement of the same joints and movements for both affected subjects did not show symmetrical results. Therefore, it is suggested that affected subjects did not make compensatory movements with both sides during both assessments with their shoulder or elbow, meaning that the compensatory movements were not visible in not affected hand. However, the compensatory movements were observed in the trunk for both subjects. The maximum movement of the upper and lower trunk lateral bending of able-bodied subjects occurred mainly in the same side as the hand that was used for the assessment, meaning that if the right hand was used for the assessment the upper and lower trunk bended into right direction resulting negative movement and the opposite for the left hand. The affected subjects showed opposite results. Lastly, affected subjects exhibited specific strategies during the assessment compared to able-bodied subjects, especially with their affected side. Those findings suggest that current prosthesis have some issues and patients might require additional training with the device. The design of the upper limb prostheses should be closer to physiological hand, especially where there is a lack of key movement of pronation/supination of the wrist in current prosthesis design. Lastly, it would be applicable to consider additional rehabilitation/training and follow up of prosthesis users.

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9 Appendix

9.1 Upward Assessment - Able-bodied Subjects

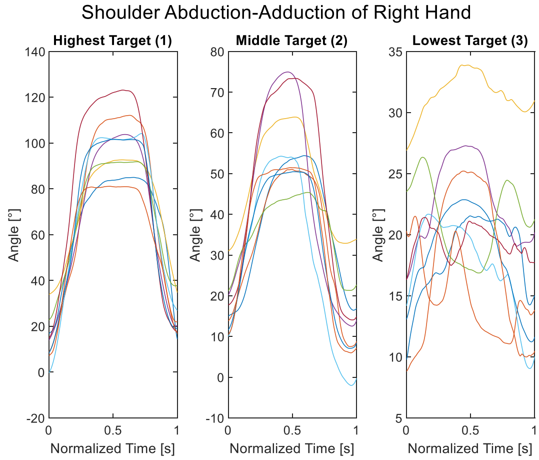


Figure 53 Shoulder abduction-adduction of right hand during upwards assessment - All able-bodied subjects.

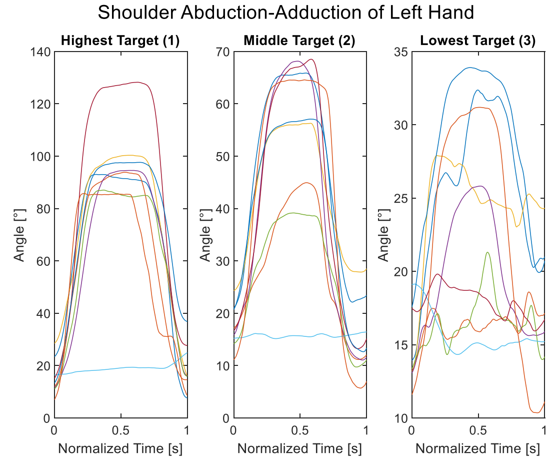
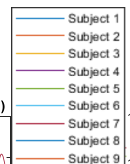


Figure 54 Shoulder abduction-adduction of left hand during upwards assessment - All able-bodied subjects.



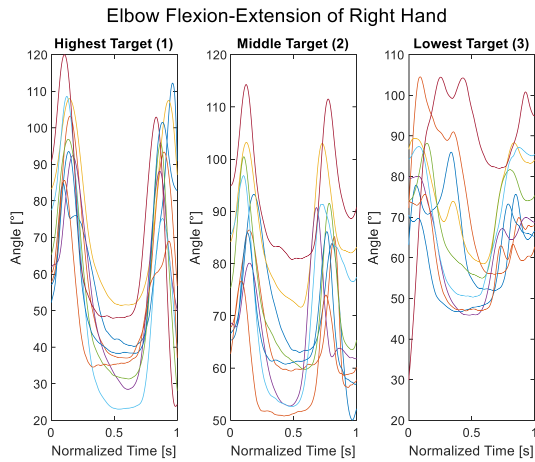


Figure 55 Elbow flexion-extension of right hand during upwards assessment - All able-bodied subjects.

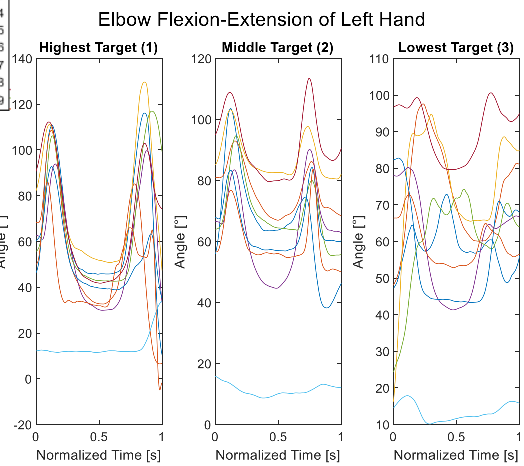


Figure 56 Elbow flexion-extension of left hand during upwards assessment - All able-bodied subjects.

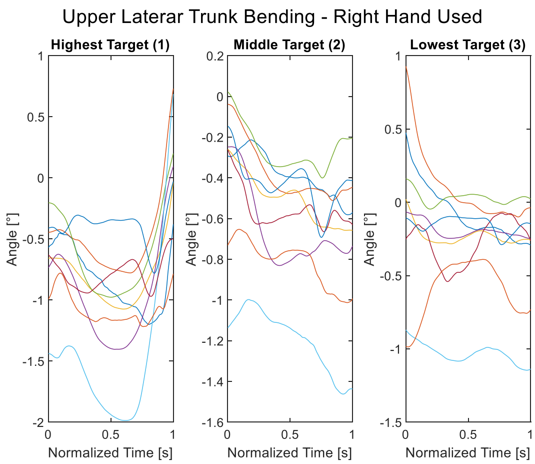


Figure 57 Upper trunk lateral bending using right hand, during upwards assessment - All able-bodied subjects.

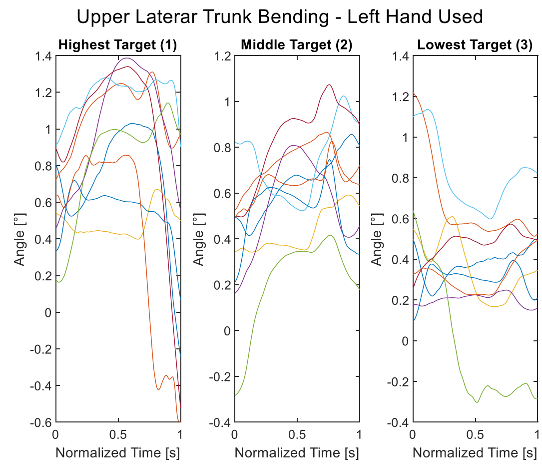
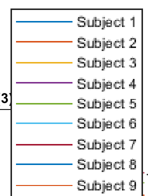


Figure 58 Upper trunk lateral bending using left hand, during upwards assessment - All able-bodied subjects.



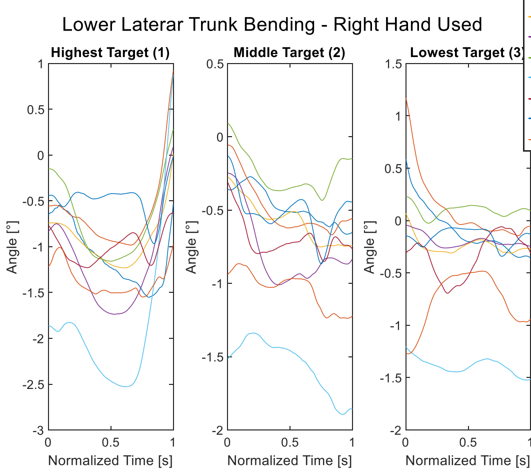


Figure 59 Lower trunk lateral bending using right hand, during upwards assessment - All able-bodied subjects.

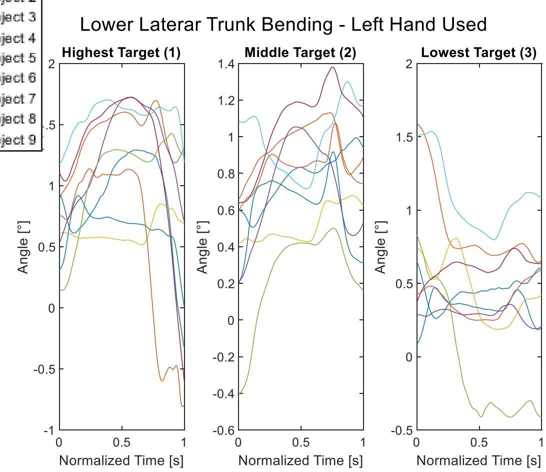


Figure 60 Lower trunk lateral bending using left hand, during upwards assessment - All able-bodied subjects.

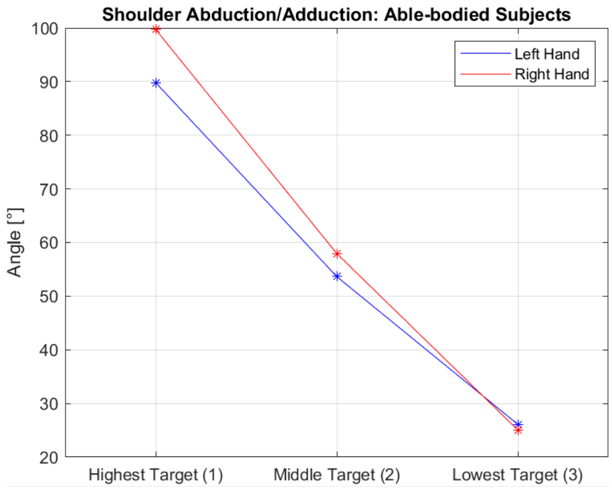


Figure 61 Comparison of shoulder abduction-adduction of left and right hand during upwards assessment - Able-bodied subjects.

Figure 62 Comparison of elbow flexion-extension of left and right hand during upwards assessment - Able-bodied subjects.

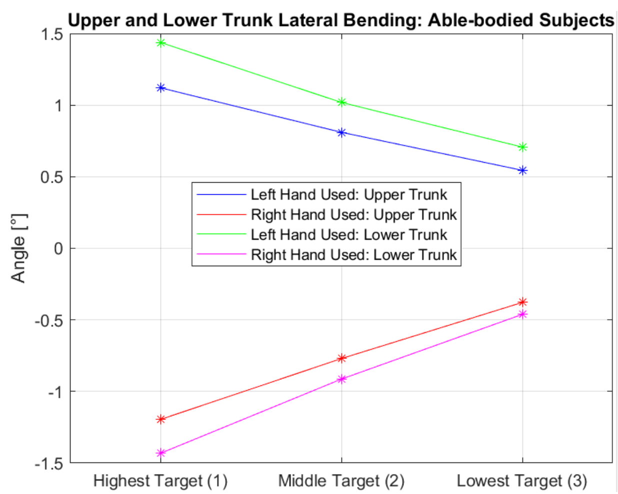


Figure 63 Comparison of upper and lower trunk lateral bending during upwards assessment - Able-bodied subjects.

9.2 Upward assessement – Affected Subjects

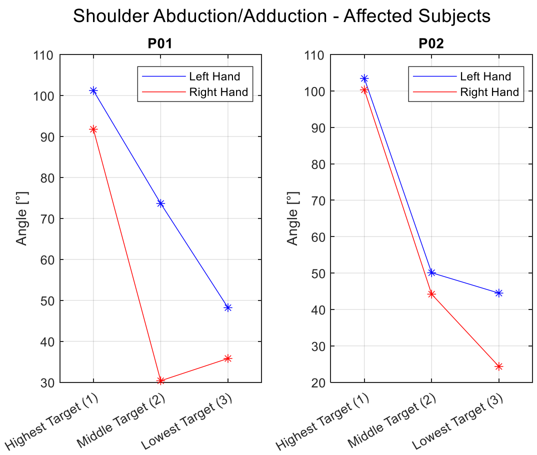


Figure 64 Comparison of shoulder abduction-adduction of left and right hand during upward assessment - Affected subjects.

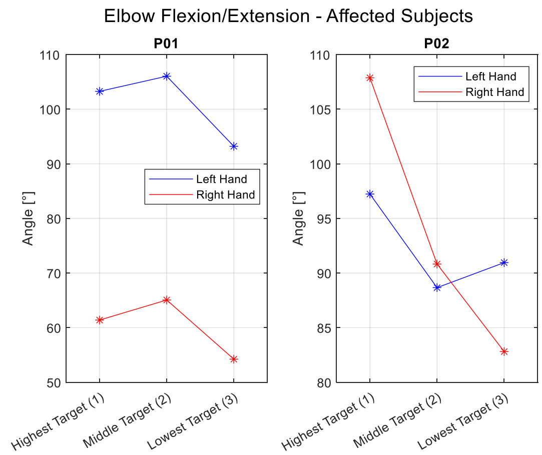


Figure 65 Comparison of elbow flexion-extension of left and right hand during upward assessment - Affected subjects.

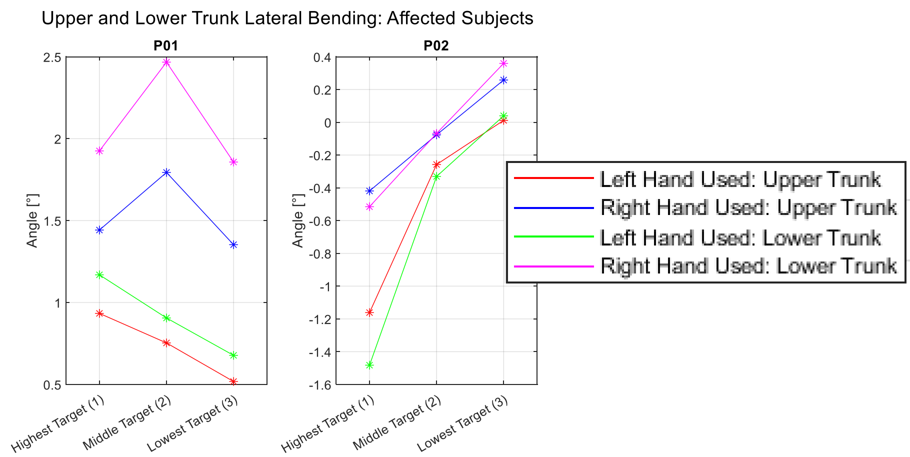


Figure 66 Comparison of upper and lower trunk lateral bending of left and right hand during upward assessment - Affected subjects.

9.3 Downward Assessment – Able-bodied Subjects

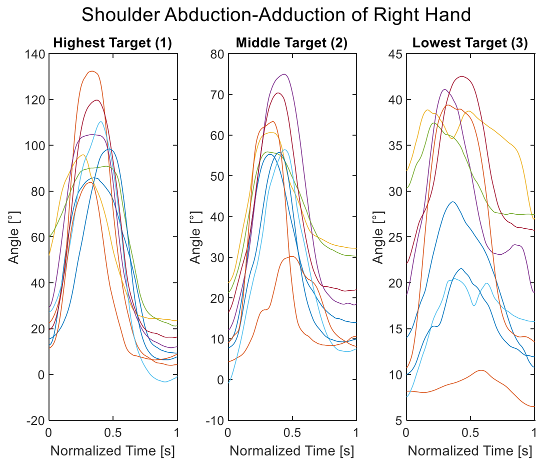


Figure 67 Shoulder abduction-adduction of right hand during downwards assessment - All able-bodied subjects.

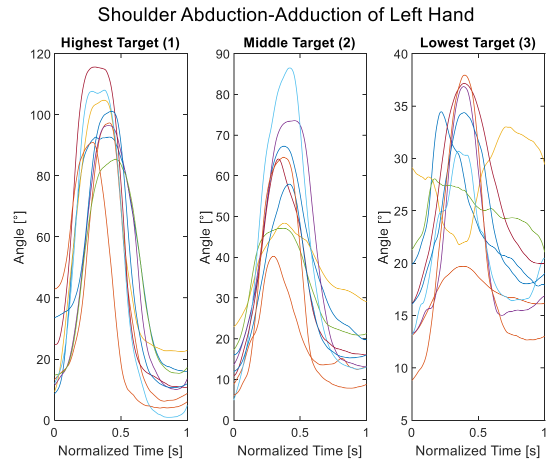
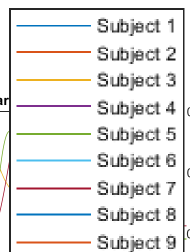


Figure 68 Shoulder abduction-adduction of left hand during downwards assessment - All able-bodied subjects.



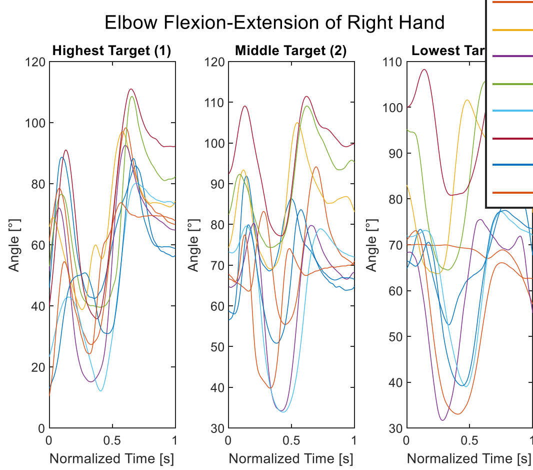


Figure 69 Elbow flexion-extension of right hand during downwards assessment - All able-bodied subjects.

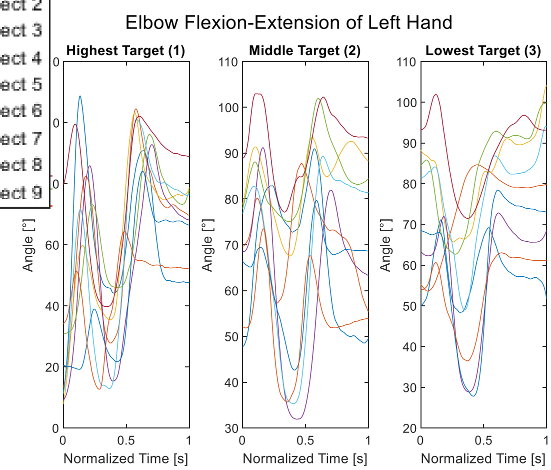


Figure 70 Elbow flexion-extension of left hand during downwards assessment - All able-bodied subjects.

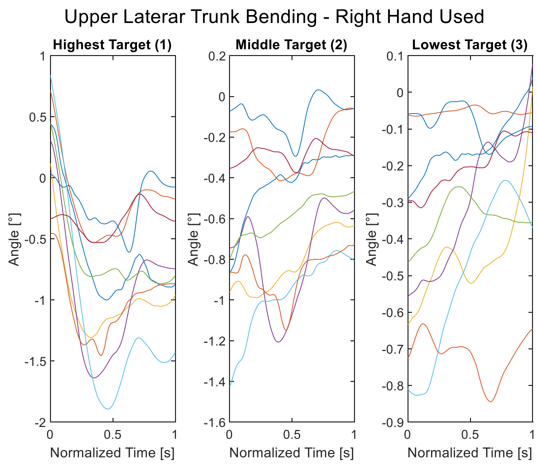


Figure 71 Upper trunk lateral bending using right hand, during downwards assessment - All able-bodied subjects.

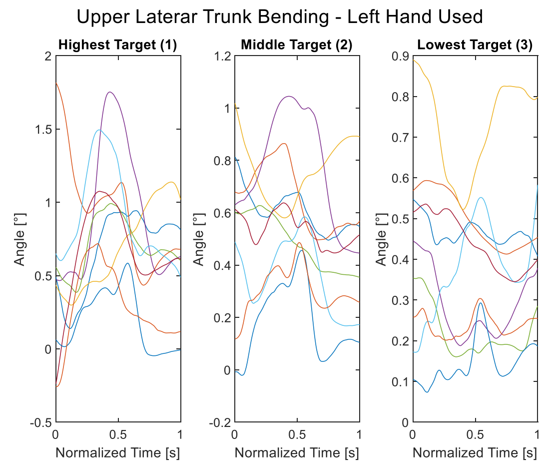


Figure 72 Upper trunk lateral bending using left hand, during downwards assessment - All able-bodied subjects.

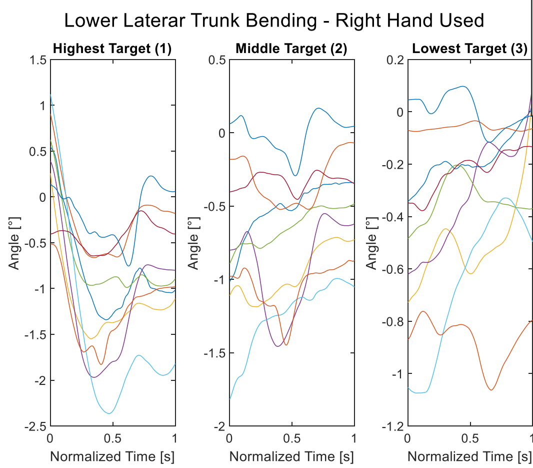


Figure 73 Lower trunk lateral bending using right hand, during downwards assessment - All able-bodied subjects.

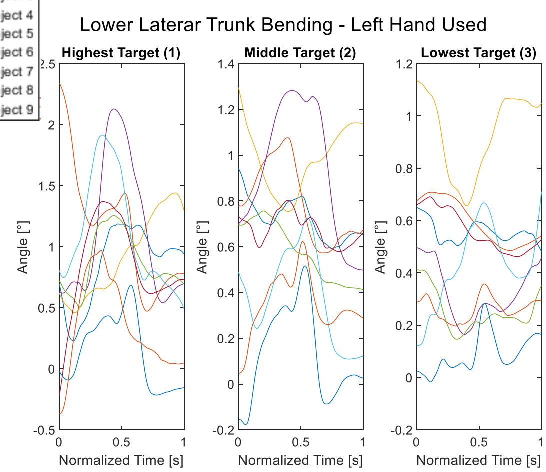


Figure 74 Lower trunk lateral bending using left hand, during downwards assessment - All able-bodied subjects.

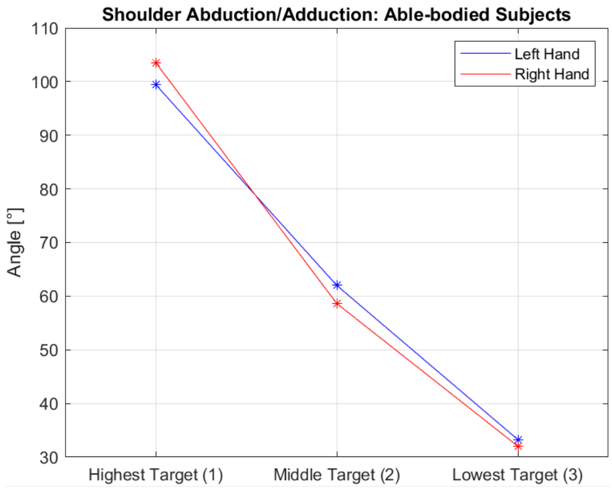


Figure 75 Comparison of shoulder abduction-adduction of left and right hand during downward assessment - Able-bodied subjects.

Figure 76 Comparison of elbow flexion-extension of left and right hand during downward assessment - Able-bodied subjects.

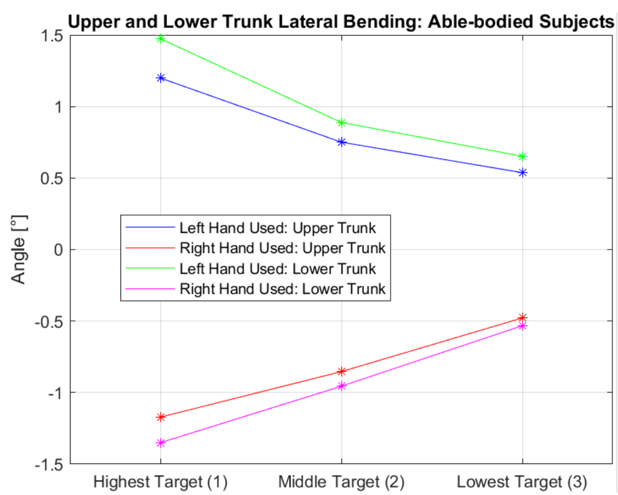


Figure 77 Comparison of upper and lower trunk lateral bending of left and right hand during downward assessment - Able-bodied subjects.

9.4 Downward Assessment – Affected Subjects

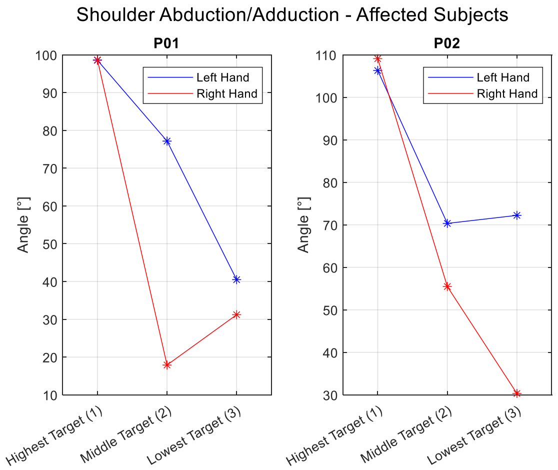


Figure 78 Comparison of shoulder abduction-adduction of left and right hand during downward assessment - Affected subjects.

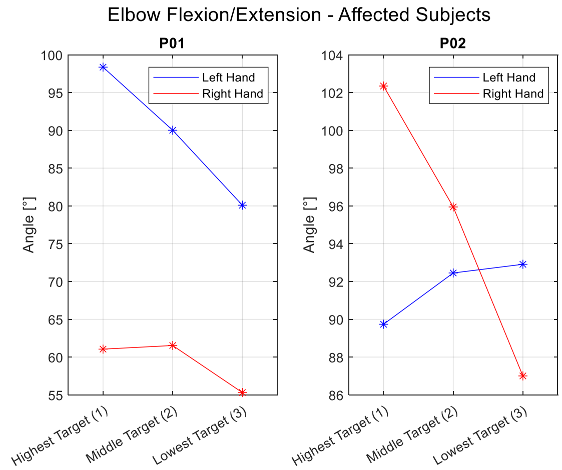


Figure 79 Comparison of elbow flexion-extension of left and right hand during downward assessment - Affected subjects.

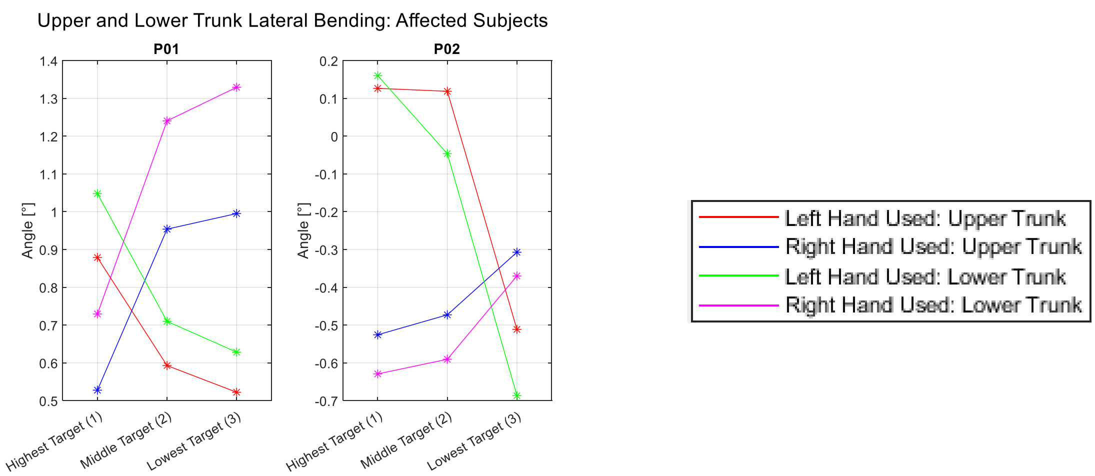


Figure 80 Comparison of upper and lower trunk lateral bending of left and right hand during downward assessment - Affected subjects.