BACHELOR THESIS

SOLUTIONS FOR POSITIONING INERTIA MEASUREMENT UNITS FOR MOTION TRACKING

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Bachelor assignment at
Xsens Technologies B.V.

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Preface

Working at Xsens Technologies has been a great experience, although very short, I've met some great people and learned alot. Working on a project that hopefully improves a product that is already one of the best on the market gives a great feeling. Always being one step ahead of the competition is a valuable asset to a company and if I have the chance to help realize that, then I can feel proud. I'm very glad I got the opportunity to work here.

Virtual reality and 3D modeling has always interested me quite a bit. Working for a company that develops, produces and sells one of the best motion capture products out there has been a priviledge. Therefore I would like to thank my colleagues for giving me this chance. First of all I would like to thank Marijke Timmermans for giving me this opportunity in the first place and for helping me out whenever I needed it (I never thought I would ever sit behind a sewing machine and actually be able to use it). Big thanks to Pietro Garofalo, Colleen Monaghan and Daniel Roetenberg for answering my questions, discussing my problems and teaching me all I needed to know about motion capture and the technology behind it. Also thanks to Giovanni Nolli who helped me with my experiments and for just being a fun guy to work with. Huge thanks to Edsko Hekman for giving me feedback and help where necessary. Lastly I would like to thank everyone here at Xsens for being so cooperative and helpful whenever I needed you.

The last three months have been a great new experience for me, I had never worked in an environment like this before so it took some time to get used to but it all turned out fine. I hope my work has been helpful and that Xsens will keep growing.

Best of luck.

Contents

Summary

Inertial motion capturing is one of a few techniques for real-time analysis of human motion. The main advantage of this specific technique is that no expensive lab and cameras are needed to get the job done. Xsens Technologies has been developing this technique for over 10 years. Their system (MVN) can be used in a number of different settings. For entertainment purposes they have developed a full-body lycra suit. For motion science purposes they have developed seperate straps that can be put onto each individual segment. This helps increase accuracy of the measurements because they can be put more tightly onto the body. It is also a one-size-fits-all solution which makes it a cheaper and easier product because only one size is needed at all times, unlike the suit. This seems like a perfect solution but there is always room for improvement, this is especially true for measurements of the shoulder. Currently the MVN Straps include some sort of shoulder top that has the shoulder sensors and sternum sensor attached to it. But because of the soft tissue artifact, complexity of the shoulder and complexity of the shoulder top, the measurements are not very accurate. The goal of this project is to find a new solution for this problem. Chapter 1 will go into more detail about this.

Chapter 2 is about the analysis phase of this project. It shows how and by who the straps are being used, how the shoulder works, what the current solutions is and what competitors have come up with. This chapter is very important to help understand the problem and what needs to be taken into account when designing a new shoulder strap.

Chapter 3 shows the design phase. To rule out some ideas, some of the old concepts and prototypes have been analyzed. These ideas did not work or were too complicated so anything similar to any of those probably would not work either. With that in mind some ideas were generated and the ones that seemed the most promising were worked out in more detail. Eventually four concepts were created. Two of them involving neoprene shoulder braces and two of them made from lycra.

In chapter 4 these concepts were eleborated into prototypes. Unfortunately it turned out that one of them was too complicated to make in the limited time that was left so only three prototypes were created. The chapter also explains and shows the results of an experiment that was conducted with the prototypes to see if any of them worked as expected and if any of them would be good enough to replace the current shoulder piece. Unfortunately the results show quite some inconsistency which made it very difficult to draw some proper conclusions from them. Results show that the neoprene prototypes do not perform very well even though people found them to be the most comfortable. Perhaps with a few adjustments it is still possible for one of the two neoprene ideas to perform better.

Chapter 1 – Introduction

To get a good understanding of what this project is all about, the problem needs to be discussed. In this first chapter a description of Xsens and its products is given. In addition some background information on the technology is described, followed by a description of the main subject. Afterwards the main goal and objective are discussed.

1.1 Problem definition

1.1.1 Xsens Technologies B.V.

Xsens is a R&D company specialized in the development of 3D motion tracking products based on miniature inertial sensor technology (microelectromechanical systems or MEMs). These products are being used in the entertainment industry (3D character animation), movement science, control and navigation of autonomous vehicles and stabilization. Ever since its establishment back in 2001, Xsens has been one of the fastest growing and most innovative companies in the Netherlands. Xsens is constantly improving its products. The main product, called MVN, is based on inertial motion capture technology. One part of this system are the motion capture straps which are mainly used for motion analysis. This is the point of focus of this report.

1.1.2 Motion Capture

Motion capture, motion tracking or Mocap can be described as the creation of a 3D representation of a live performance (Metamotion, 2012). It is the process of recording movement and translating that movement onto a digital model. The best known application for mocap is the entertainment industry (films and games). Movement of actors is recorded using mocap techniques. This animation data is then mapped to a 3D model so that the model performs the same actions as the actor.
However, this is not the only application for mocap. It is also being used in i.e. the military and sports. Scientists use the technique to analyze human motion (i.e. gait analysis). Medical professionals apply mocap to interpret movement patterns of disabled patients for the planning of treatment protocols. Athletes and coaches use motion capture to improve performance without causing injury (Roetenberg, 2006). And there are many more uses for motion tracking.
Mocap has been around since the late 1970s and quite a few techniques have been developed since, each with its own strengths and weaknesses. Not a single technology is perfect for every application.

Magnetic motion capture

Magnetic motion capture uses sensors placed on the body to measure the low-frequency magnetic field generated by a transmitter source. The strength of the signal is proportional to the distance between the emitter and sensor. Specific software is then able to calculate the position and orientation of the sensor based on the signal strength. Because these systems usually do not use many sensors, 6 to 11, the technique relies greatly on inverse kinematics to get the animation right and adjustments need to be made afterwards. Also when sensors from different actors come close to each other, they will interfere and provide inaccurate results. Another drawback is that the system has negative reactions to metal or magnetic fields making it impossible to use in an environment with a lot of metal structures (in buildings) (Metamotion, 2012; Roetenberg, 2006).

Optical motion capture

One of the most frequently used mocap techniques is optical motion capture. There are basically two main technologies: passive and active optical motion capture. Passive mocap relies on reflective markers placed on particular parts of the body while active mocap relies on pulsed-LEDs attached to the body. Both techniques use cameras to capture the movement of the markers resulting in several 2D images. Using a triangulation technique, a computer is able to calculate the 3D position of the markers in every frame. Optical motion capture can result in very accurate animations but has the drawback of suffering from blocked markers by for example the actor himself. Also other light sources or reflections can cause problems. Another drawback is the post-processing, it can take a long time for the information to be processed. The advantage is that it can be used on pretty much anything, the technique is not limited to just the human body, markers can be placed on anything (Metamotion, 2012; Roetenberg, 2006).

Electro-mechanical motion capture

Electro-mechanical mocap makes use of an exoskeleton that links the user's joints together with rigid or flexible linkages. Goniometers within these linkages measure the angle of the joints. This data can then be used to determine the user's body posture. It is quite an accurate technique but the drawback is that it is very restrictive and alignment with body joints can be difficult (Roetenberg, 2006).

Acoustic motion capture

Acoustic motion capture uses audio transmitters on the user's body that send out ultrasonic pulses when activated by movement. Receivers measure the time it takes for the pulse to reach them and triangulate the data to indicate a point in 3D space. While this method does not suffer from the line-of-sight issue that optical mocap suffers from, the tracking can be disturbed by audio interference and reflections of the sound (Roetenberg, 2006).

Inertial motion capture

Inertial mocap is similar to the human inner ear. The inner ear is a biological 3D inertial sensor in the sense that it can measure angular motion and linear acceleration of the head. An inertial sensor works in the same way. A gyroscope measures angular velocity and an accelerometer measures linear accelerations. These measurements can be used to calculate angle, velocity and motion or orientation of the measured segment (Roetenberg, 2006). This method allows for great freedom of use and does not require an expensive and complex lab. Measurements can be obtained in a natural environment. However, this technique lacks the accuracy that can be obtained by for example optical motion capture due to electronic noise. More information on the sensors or IMUs (inertial measurement units) can be found in appendix A.

Markerless motion capture

The latest innovation in the field of mocap is markerless motion capture. All of the above technologies apart from optical mocap can be considered markerless but the technology described here does not require sensors or a suit at all. Multiple 2D video cameras are needed to track the subject. The obtained data is processed by a vision processor which maps every pixel of information and triangulates the location of the subject by seeing where the various camera images intersect (Organic Motion, 2012). This results in full 3D model of the subject with 3D bone movement data down to millimeter precision. An example of a system that uses a technology kind of like this is Kinect for Xbox 360. However, since this technology is quite new, it has not been fully developed yet.

1.1.3 MVN Straps vs. MVN Suit

MVN is the name of the technology developed by Xsens for motion capturing. It makes use of the inertial motion capture technology. Before the straps were introduced Xsens used a full-body lycra suit that had several inertial measurement units (IMUs) attached to it to be able to register the movement of all major body segments. These suits work well for most applications but also have their disadvantages, which is why the straps were introduced and developed. The straps are a more flexible system that is more suitable for measurement of individual limbs. Some possible situations that require the use of these straps:

- In case of large test groups, different sizes and smelly suits can lead to a continuing time-consuming exchange of the system from suit to suit. The straps are a one-size-fits-all system and can be swapped quickly and easily from person to person.
- When tests involve very strict hygiene requirements, which for example do not allow skin contact, straps will give an outcome as they are easily worn over clothing.
- Straps are easier to put on than a full-body suit if a patient is physically challenged.
- If a person has an unusual body physique which does not allow him to wear the suit properly, the straps are a perfect solution because every strap can be adjusted individually.

The straps are developed specifically for each body segment to optimize the attachment of each sensor (figure 1.1). There are three possible configurations, each having a specific strap set:

- Full body system;
  - 2 x foot mounts;
  - 2 x lower leg: left & right;
  - 2 x upper leg: left & right;
  - Pelvic belt;
  - Shoulder piece;
  - 2 x upper arm: left & right;
  - 2 x forearm: left & right;
  - 2 pairs of gloves: size M and XL;
  - Head band;
  - 12 x cable guides 5 cm;
  - 6 x cable guides 2,5 cm;
- Upper body system;
  - Pelvic belt;
  - Shoulder piece;
  - 2 x upper arm: left & right;
  - 2 x forearm: left & right;
  - 2 pairs of gloves: size M and XL;
  - Head band;
  - 6 x cable guides 5 cm;
  - 3 x cable guides 2,5 cm;
- Lower body system;
  - 2 x foot mounts;
  - 2 x lower leg: left & right;
  - 2 x upper leg: left & right;
  - Belt pelvis;
  - 6 x cable guides 5 cm;
  - 3 x cable guides 2,5 cm;

When the customer only needs to analyze certain body parts, this setup makes it possible to buy only those sensors he or she needs. This makes it more affordable and reduces the set up time because the user will not have to put on an entire suit. In the future there will even be more options available. Xsens is working on new products that allow costumers to only buy sensors and straps for the segments they need to do research on.

This project does not focus on all of the straps; it merely focusses on the shoulder piece because it is not working properly the way it is designed now. The shoulder piece should keep the tracker on the correct position and allow it to follow the motion of the scapula. This, however, is very difficult because of the soft tissue artifact and the fact that the scapula moves underneath the skin. In other words, it is very difficult to precisely follow the movement of the scapula. The current shoulder piece does not meet the standards that Xsens needs partly because of its one-size-fits-all requirement. This makes the shoulder piece quite complex. A solution needs to be found that more accurately follows the movement of the scapula.

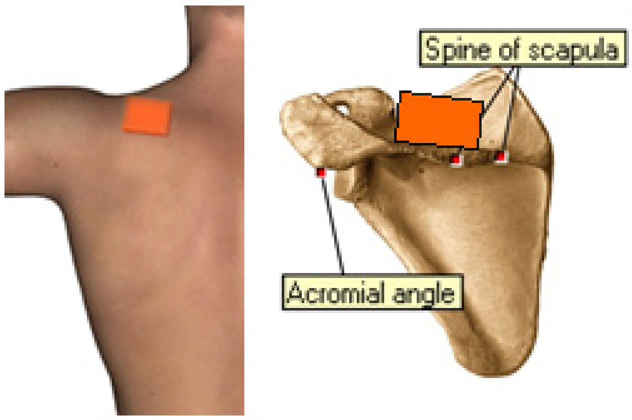

Figure 1.1 (left) MVN BIOMECH or MVN Straps.

Figure 1.2 (above) Placement of the IMU on the shoulder with the current shoulder piece.

1.1.4 Soft Tissue Artifact

The best way to measure human motion is to measure motion of the bone. This is exactly what Xsens is trying to do with their IMUs. The IMUs are placed on a segment (i.e. upper arm, lower leg, etc.) in such a position that it relatively accurately measures the movement of the underlying bone. However, the so called soft tissue artifact (STA) makes measuring bone movement very difficult. Soft tissue artifact refers to the sensor's incorrect replication of bone motion due to muscles, fat and skin (and in the case of straps also clothes) that lies between the bone and sensor (or marker) (Della Croce, 2006; Cao L. et al., 2007).

The soft tissue artifact is different for every person and is task specific and is therefore hard to capture. Skin deformation depends on the subject's physical characteristics, location of the sensor and performed movement. In addition, when the subject is moving, muscle contraction and flexion have a big impact on the soft tissue artifact which causes the sensor to move differently than the bone.

The soft tissue artifact is particularly present in the shoulder joint and shoulder girdle. Not only soft tissue is an issue in this joint, also the bone has the tendency to slide underneath the skin, this is particularly true for the scapula. This happens in general with almost every bone, but it is the most obvious for the scapula. Because of the complexity of the shoulder joint a proper solution to counter the STA has not been found yet. In general several solutions have been tried but none of them fixed the problem entirely.

For the soft tissue artifact to be reduced to a minimum it is best for the sensor to be placed on a bony landmark where the tissue between the sensor and bone is relatively small. The sensor also needs to be placed on a more or less flat surface to keep it stable because it is quite big. This is difficult to accomplish on the shoulder because of its anatomy. A solution for this problem needs to be found.

1.1.5 Shoulder piece

The main function of the shoulder piece is to keep the shoulder trackers in place. The correct position for these trackers has been defined as just above the spine of the scapula (figure 1.2). This placement has been chosen because the soft tissue artifact occuring in the shoulder seems to be relatively small in that area. The spine of the scapula is also a nice guide for the tracker, it offers stability and keeps the tracker in place. More on that in chapter 2.

Unfortunately, because the shoulders are very complex joints, the current shoulder piece does not perform well enough. The problem lies with the STA and primarily in the fact that the bone and joint slide underneath the skin which results in misinterpretation of the movement by the sensor. The effect of this problem is clearly seen in the unprocessed performance of the 3D character. When the hands of the performer are placed together after calibration, the character shows crossed hands or distance between the hands. The accuracy of the position of the hands is to a large extend determined by errors in the shoulder model. When elevating the shoulders with the upper arms (shoulder abduction and/or flexion), the shoulder angle is often underestimated. For example, in the sequence of poses shown in figure 1.3 the subject is holding his hands together during each pose. In the measured kinematic chain, the hands do not touch. A new shoulder piece is required to be able to make better measurements of the shoulder's rotation which should result in a more proper position of the hands. The closer the hands are together, the better the result.

The current shoulder piece also has the sternum tracker attached to it because it is a very important tracker for proper relative positioning of the shoulder joint in the 3D model. Adding this tracker to the shoulder piece also makes the entire product less complicated, there is no need for an extra strap on top or below the shoulder piece. Although this does make the actual shoulder piece more complex and perhaps make the measurements less accurate. Preferably this function needs to be maintained in the new solution.

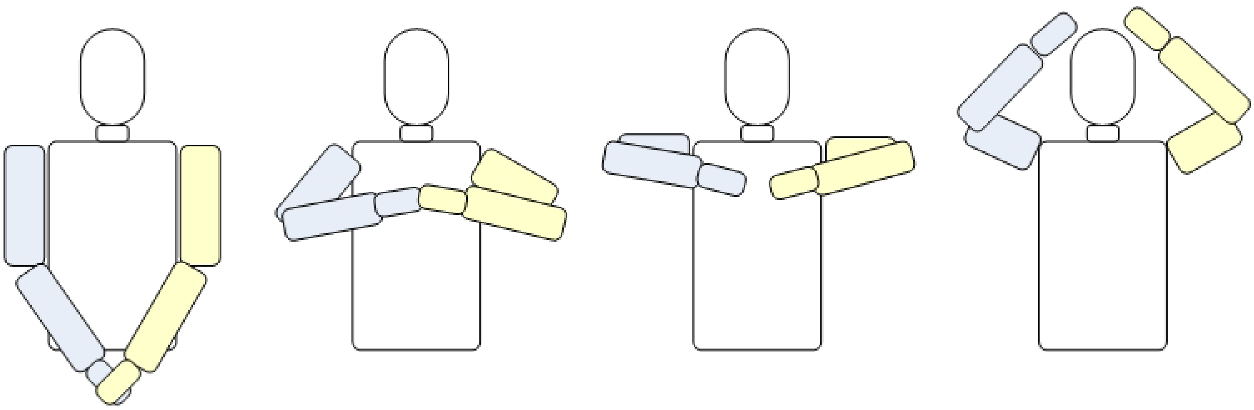

Figure 1.3 Visualization of the problem. The subject is holding his hands together but in the measured kinematic chain the hands do not touch.

1.2 Goal and objective

The goal of this project is to find a way to optimize measuring of scapular rotation using the MVN Straps and inertial motion trackers. The anatomy of the shoulder prevents the sensors from making accurate measurements which results in a mismatch between actual and calculated motions. The soft tissue artifact should be minimized as good as possible while keeping freedom of movement and user friendliness in mind. The new shoulder piece needs to keep the shoulder sensors in the correct position while allowing them to follow the movement of the scapula as accurate as possible.

Changes in software might help to improve results as well but that is beyond the scope of this project. The focus is on the shoulder piece itself.
Position of the sensors is also not part of this project. Xsens has determined the best possible position for the sensors and it is advised to keep using that postion.
The current piece also has the sternum tracker attached to it. Preferably the new solution also includes this sensor.
Also, minimization of possible errors in placing the sensors on the body should be kept in mind.
The project should lead to a solution that is both functional and user friendly as well as comfortable.
To help achieve this goal, several questions and sub-questions have been set up as a guide throughout the project.

- What is the current problem with the shoulder tracker?
  - Where is the shoulder tracker positioned?
  - What problems occur with this position?
  - How is the shoulder tracker attached?
  - What problems occur with this attachment?
  - What is the cause of those problems?

- How does the shoulder work?
  - What is the anatomy of the shoulder?
  - Which movements is the shoulder joint able to make?
  - Which shoulder movements cause the most problems when measuring with MVN Straps?

- How can the shoulder tracker be attached at the right position?
  - What has Xsens tried already?
  - Which solutions did competitors come up with?
  - How can a shoulder piece preserve the freedom of movement of the user?
  - How does the shoulder tracker stay stable on its position?
  - How can a shoulder piece preserve the user friendliness?

- In what way does the investigation result in an optimal solution?
  - Is the soft tissue artifact being reduced?
  - Does the shoulder tracker stay in the right position?
  - Does the freedom of movement stay preserved?
  - Is the strap user friendly?

It needs to be stated that a perfect solution might not be possible. The ultimate goal of this assignment therefore needs to be defined as an investigation to the possibilities of improvement of shoulder tracking. There is a possibility that the current shoulder piece still seems to give the best results. If this is the case than it would be unwise for Xsens to change anything, but at least it has been thoroughly investigated.

Chapter 2 – Analysis phase

To get a good understanding of the problem it is necessary to investigate the shoulder piece and the shoulder itself. Having some knowledge on the shoulder anatomy and the possible movements of the shoulder is also important. This can be used to come up with a concept that is user friendly and keeps the freedom of movement high enough.
Use of the MVN Straps is also an important factor to analyze. It is very hard to come up with new solutions if it is not known what people do with the straps and what people want.
Also the competition for Xsens' strap based mocapping is analyzed, perhaps other mocap companies have found good solutions to deal with the problems occurring with the shoulder straps.
This will ultimately result in a list of requirements.

2.1 Shoulder analysis

2.1.1 Anatomy of the shoulder

Bones

The shoulder is a very complex joint. It does not consist of a single joint but it is rather a complex arrangement of bones, ligaments, muscles, and tendons that is better known as the shoulder girdle or the pectoral girdle. The upper extremity can be divided in two parts. The shoulder girdle includes two bones: the scapula (shoulder blade) and the clavicle (collar bone) and the arm, which includes the humerus (upper arm bone) (figure 2.1) (Platzer, 2003; Healthpages, 2010).

Scapula

The scapula is the most complex of the bones in the shoulder. The scapula is a flat, roughly triangular shaped bone that floats on the rib cage, and is attached to it only with muscles. There are three landmarks on the scapula; the spine, acromion and coracoid processes. The roof of the glenohumeral joint is formed by the acromion. The acromion articulates with the clavicle forming the acromioclavicular (AC) joint. A spine divides the back of the scapula into two sections. The muscles that attach below this spine are called infraspinatus muscles; the ones that attach above this spine are called supraspinatus muscles.

Clavicle

The clavicle is an 'S'-shaped bone that originates at the sternum (breastbone) just above the first rib, and is held in place by the acromioclavicular ligament, several muscles and the coracoclavicular ligament. The clavicle helps hold the shoulder out to the side while allowing the scapula to move around.

Humerus

The humerus is connected by joints to the scapula and the radius and ulna. The top of the humerus is the ball part of the ball-and-socket joint. The head (ball) of the humerus is fitted within the glenoid fossa (socket) located on the scapula. Below the humeral head is the anatomic neck which separates the head (ball) from the tuberosities; the greater tuberosity and the lesser tuberosity. Each tuberosity provides a place for the attachment for the muscles of the rotator cuff—the 4 rotator cuff muscles act to stabilize the shoulder. Just below the tuberosities is the surgical neck of the humerus and is the most common area for fractures of the proximal humerus. Below the surgical neck the deltoid tuberosity starts to which the deltoid muscle attaches.

Joints

There are four joints making up the shoulder girdle. One joint is where the head of the humerus articulates inside the glenoid cavity of the scapula, called the glenohumeral joint which includes the ligaments, tendons and muscles attached to these two bones. The acromioclavicular joint (AC Joint) includes the ligaments, tendons, and bones where the acromion (on the shoulder blade) joins at the clavicle. The third joint is the sternoclavicular joint which forms where the sternum (breastbone) joins the clavicle. The final joint is the scapulothoracic joint, where the scapula meets with the ribs at the back of the chest (figure 2.2).

The glenohumeral joint

The glenohumeral joint provides most of the motion in the shoulder girdle. It is a ball-and-socket joint like the hip joint. The large, almost perfectly round head of the humerus fits into the small, shallow glenoid socket on the lateral (outside) side of the scapula. Due to the very limited interface of the humerus and scapula, it is the most mobile joint of the human body. However, this also makes the joint fairly unstable. Therefore, it is the soft tissues in the joint that maintain stability and mobility.

The acromioclavicular joint

The AC joint is a joint at the top of the shoulder. It is the junction between the acromion and the clavicle. This joint helps link the arm to the body at the chest. Since there is not much bony stability in this joint, soft tissues and some ligaments are needed to stabilize this joint. The superior AC ligament is the most important horizontal stabilizer. The coracoclavicular ligaments help stabilize the clavicle vertically.

The sternoclavicular joint

The SC joint joins the clavicle to the sternum. Most of the rotation of the shoulder girdle occurs at the sternoclavicular joint and joint stability comes from the soft tissues. The posterior sternoclavicular joint capsule is the most important structure for preventing forward and backward displacement of the medial clavicle.

The scapulothoracic joint

The ST joint joins the scapula with the back of the rib cage. The joint allows for increased shoulder elevation.

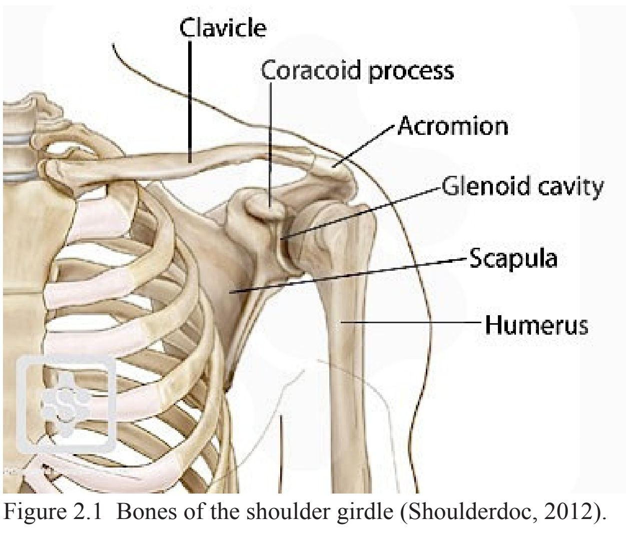

Figure 2.1 Bones of the shoulder girdle (Shoulderdoc, 2012).

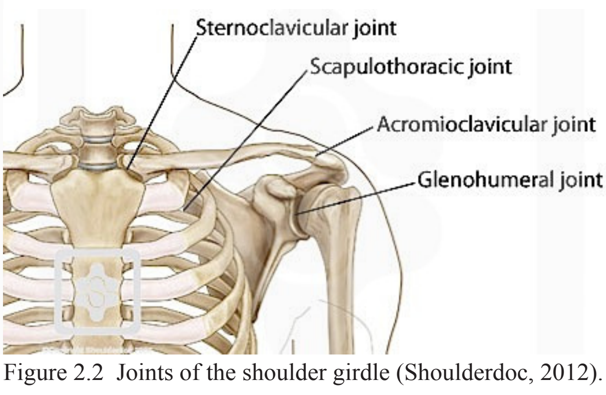

Figure 2.2 Joints of the shoulder girdle (Shoulderdoc, 2012).

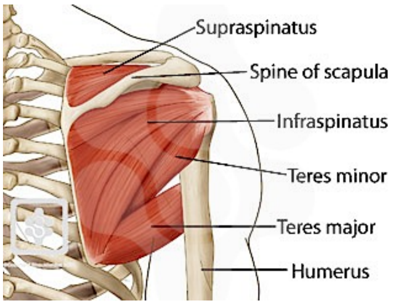

Figure 2.3 Rotator cuff muscles (Shoulderdoc, 2012).

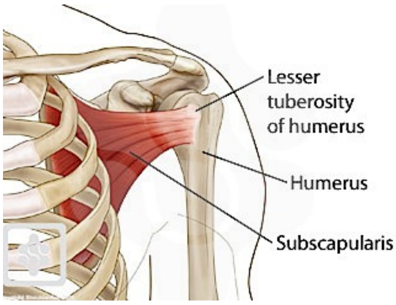

Figure 2.4 Rotator cuff muscles (Shoulderdoc, 2012).

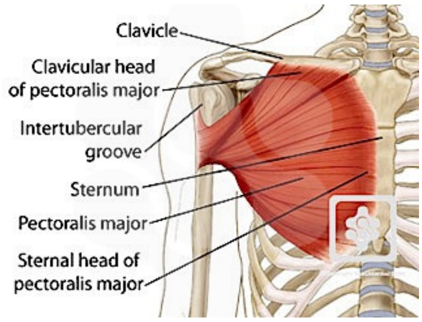

Figure 2.5 Pectoralis major (Shoulderdoc, 2012).

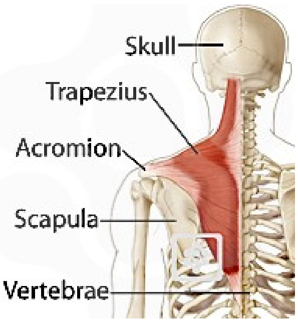

Figure 2.6 Trapezius (Shoulderdoc, 2012).

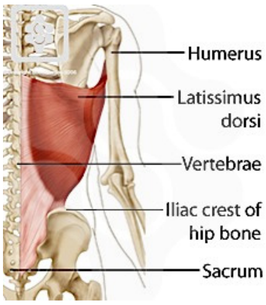

Figure 2.7 Latissimus dorsi (Shoulderdoc, 2012).

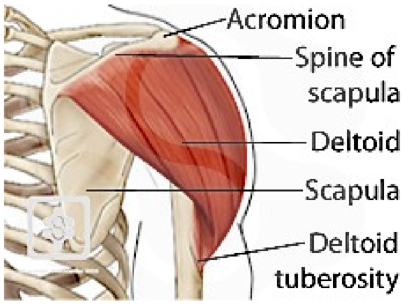

Figure 2.8 Deltoid muscle (Shoulderdoc, 2012).

Muscles

Muscles in the back, neck, shoulder, chest and upper arm all work together to support and move the shoulder. Each muscle of the shoulder assists with specific movements. The deep muscle group are the rotator cuff muscles and tendons. Keeping the head of the humerus inside the glenoid fossa is the primary function of the rotator cuff muscles. This important group of muscles lies just outside the glenohumeral joint and helps rotate the shoulder in the many directions. The rotator cuff muscles include the supraspinatus, infraspinatus, teres minor muscles and subscapularis (figure 2.3 and 2.4).

Above the rotator cuff muscles there are four more muscles that are responsible for shoulder movement. On the front (anterior) side there is the pectoralis major (figure 2.5). On the back (posterior) side there are the trapezius muscle (figure 2.6) and the latissimus dorsi (figure 2.7). And on the side there is the deltoid muscle which provides the characteristic contour of the shoulder and is the largest and strongest muscle of the shoulder (figure 2.8).

(Platzer, 2003; Healthpages, 2010; Shoulderdoc, 2012)

2.1.2 Movements of the shoulder

There are a couple of different ways to move the shoulder. There are the movements involving the scapula and the clavicle which include elevation, depression, abduction and adduction of the shoulder girdle. And there are movements involving the glenohumeral joint which include abduction, adduction, flexion, extension and external and internal rotation. Most movements cannot be performed by just one joint, a combination of joints and muscles are needed to complete an entire motion. On the whole, the shoulder is able to execute the following movements:

- flexion-extension: around the transversal axis (figure 2.9);
- horizontal flexion-extension: rotation around a vertical axis (figure 2.9);
- ab-adduction: around the sagital axis (figure 2.10);
- internal-external: around the long axis of the arm (figure 2.11);
- protraction-retraction: forward and backward shift of the entire complex (figure 2.11);
- elevation-depression: vertical drifting of the complex (figure 2.11).

An important fact for this project is that flexion-extension and ab-adduction are movements that come from both the humerus and the scapula, it is the so called scapulohumeral-rhythm. It refers to the coordination between the glenohumeral and the scapulothoracic joint. During the first 30°-60° of flexion the scapula has an irregular motion which depends on the steady state. In the next phase of the movement the motion ratio between the two joints is about 2:1. Recent studies, however, show a different ratio: 4.3:1 for the first 30° and 1.25:1 from 30° to 180°.

(Bray, 1958; Cutti, 2006)

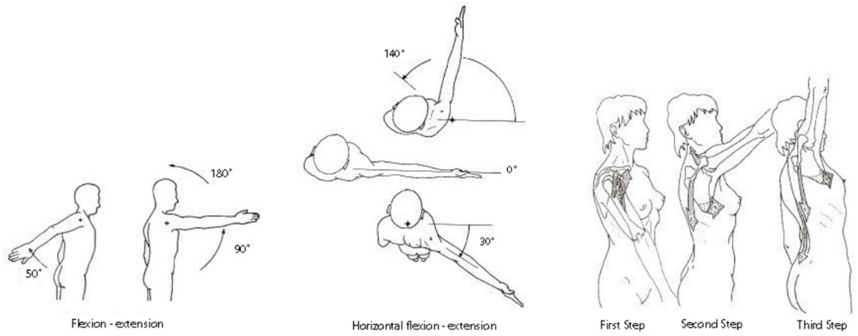

Figure 2.9 Shoulder flexion-extension and horizontal flexion-extension.

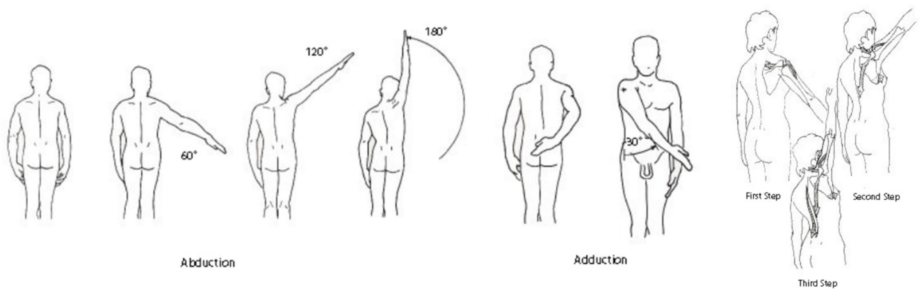

Figure 2.10 Shoulder abduction-adduction.

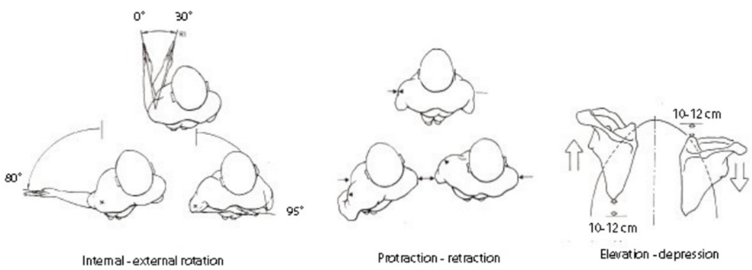

Figure 2.11 Shoulder internal-external rotation; protraction-retraction and elevation-depression of the entire complex.

2.1.3 Soft tissue artifact

Soft tissue artifact and bone sliding underneath the skin is the biggest problem for capturing movement of the scapula. As can be seen in figures 2.3 - 2.8 the shoulder joint is completely covered in several layers of muscle tissue. When moving the shoulder these muscles flex or contract causing unwanted movement of the tracker that is put on the shoulder. The only obvious bony landmark that can be used to put a tracker on to minimize the STA is the acromion. However, putting a tracker the size of a matchbox on top of the acromion causes stability problems. Therefore it has been decided to put the tracker on a position that has the least amount of soft tissue, namely just above the spine of the scapula. There are two muscles present at that position. On the deepest layer there is the supraspinatus which is right against the scapula. It helps the deltoid with abduction of the arm and it stabilizes the shoulder by drawing the humerus toward the glenoid fossa. The other muscle is the trapezius which is the biggest problem in that area concerning STA. It plays a big part in rotation, retraction, elevation and depression of the scapula. Part of the trapezius is connected to the top part of the spine of the scapula. The tracker is placed on top of this connection (figure 2.12). The trapezius bulges when moving the arm and will inevitably move the tracker but this might be reduced to a minimum if the tracker is put tightly on the body.

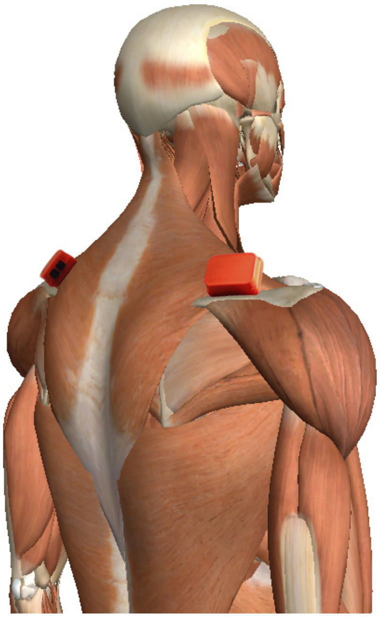

Figure 2.12 Position of the sensor on the trapezius.

2.1.4 Scapular motion

As far as the scapula sliding underneath the skin, this is quite obvious and can be seen just by observing someone's shoulder. Figures 2.9 - 2.11 also show the complex range of motion of the scapula during the most basic arm movements. It is very difficult to capture scapular motion by placing a tracker or marker on the skin. Studies from 2005 have concluded that measurements can be off by as much as 86 mm depending on the type of movement and placement of the tracker. This study used optical markers on the skin to measure the position of the scapula on seven different locations and MRI to measure the actual position of the scapula. The scientists put the markers on the skin with the scapula in starting position (arm at the side of the trunk). Then the subject was asked to move the arm to a certain position and the position of the markers was compared to the actual position of the scapula measured using MRI. The marker that represented the placement of the tracker as described in paragraph 2.2.3 had an error of 21.0 mm ± 16.1 mm when moving the hand behind the back and an error of 63.2 mm ± 16.5 mm when elevating the arm (Matsui et al. 2005). These results were the second best. The best results came from the trackers placed on the acromion, but as stated before, this is not an ideal position for a tracker. Xsens has chosen for the best possible position according to this study even though the errors are still quite big. But hopefully the errors that still occur can be reduced if the tracker is somehow strapped tightly to the scapula.

2.2 Current solution

2.2.1 Current shoulder piece

The current MVN shoulder piece is a small vest made from lycra just like the MVN suits (figure 2.13). It has to be put on from the front and can be fastened at the back with a Velcro strap.
Another set of straps is added at the bottom of the vest that is there to keep the sternum tracker in place.

On top of the shoulders another set of straps (PP band) have been added which can be secured to the upper arm straps. They put tension on the lycra in all directions to push the sensor onto the bone.
The front of the top has another piece of material added into it which has the sternum tracker attached to it.
The shoulder trackers can be put into their respective holders which are integrated in the vest in the position for placement along the spine of the scapula.

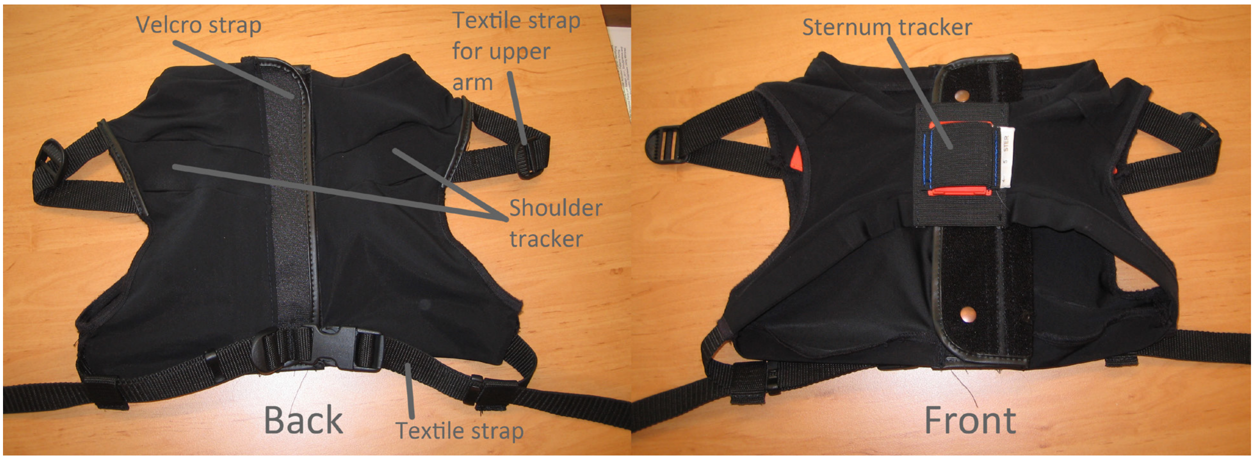

Figure 2.13 The current shoulder top.

2.2.2 Problems

After talking to some experts at Xsens (Pietro Garofalo, Daniel Roetenberg, Colleen Monaghan and Giovanni Nolli), a number of problems with the current shoulder piece were listed.
The biggest problem is of course the accuracy. The vest does not allow for precise and accurate measurements of the scapula. Soft tissue artifact is partly to blame for this but the piece could also be improved.
Another problem is the Velcro strap at the back. Because of its size it is not very comfortable and it can greatly affect measurements.
Because of its complexity it is easy to become confused about the orientation of the vest. Untrained people might try to put it on upside down.
It is very difficult to put on the vest by yourself because it needs to be secured at the back. There are researchers who work on their own and do not have anyone to help them put it on.
Another problem is when women have large breasts. The sternum tracker could get affected by them.
The one-size-fits-all requirement also causes some problems. Even though the vest stretches quite a bit it still does not fit everyone. Many people are too small (for example many Asians) while others are too big (athletes).

2.3 Strap size

The current vest is a one-size-fits-all piece of garment. This was a requirement back when Xsens first came up with the idea of making a strap based system. It gives the product a unique selling point in the sense that costumers would have to buy only one set of straps and everyone would be able to wear it. However, it turns out that this requirement causes a lot of the issues concerning the accuracy of the trackers. Therefore Xsens is thinking about getting rid of that requirement and make different sizes just like the suits.
To determine whether the current vest is really one-size-fits-all or not, and whether it would be better to have different sizes, a test has been done. This test has been done within Xsens, 32 people cooperated. They put on the vest and the Velcro part at the back that is left over was measured. This was the way to determine whether the vest fit or not. Apart from that measurement the chest circumference and shoulder width were also measured just in case it would be decided to implement multiple sizes.

The results show that about 70% of the people fit the vest. However, this is not a very accurate percentage because Xsens' costumers come from all over the world. Asians for example are generally smaller people, the sales department said that the vest is too big for most Asians. On the opposite side, athletes are usually bigger, have broader shoulders, for them the vest is often too small. Thus the amount of people fitting the vest will be even lower than 70%. If the one-size-fits-all requirement stays than that means that the new shoulder piece will have to be even more elastic and have more adjustable straps than the current piece, which is already very elastic. Adding more elastisity and adjustable straps will most likely result in less accuracy as well.
After a discussion with several people from Xsens it has been decided that the new shoulder piece does not necessarily need to be one-size-fits-all. However, if the final solution somehow allows for one-size-fits-all than that can be proposed. Results of the test can be found in appendix B.

2.4 Competition

Xsens's approach towards motion capture using inertial motion capture technology is quite unique but several companies have started in the past couple of years and are now direct competitors with the MVN system (figure 2.14).
MVN competitors include a series of optical mocap providers as well as inertial mocap providers. Since optical mocapping works quite differently, these companies will not be discussed unless their system features some sort of shoulder or chest strap.

IGS by Animazoo

Animazoo has two types of suits based on inertial motion capture technology: the IGS-150 and the IGS-180. The IGS-150 features 15 inertial gyroscopes that accurately capture full body motion, while the IGS-180 features 18 of these gyroscopes (Animazoo, 2012). Both suits are very similar to the MVN suits. Animazoo also has the IGS-Mini which is a system very similar to the MVN straps. The system is ideal for researchers when specific areas of body movement need to be analysed. There are four configurations possible: IGS-30, IGS-40, IGS-70 and IGS-120. The IGS-30 is ideal for measuring the rotations of a subject's arm. The IGS-40 is ideal for measuring the rotations of a subject's leg. The IGS-70 is ideal for measuring the lower half of a subject's body and the IGS-120 is ideal for measuring the upper half of a subject's body. Unfortunately there is no information available on the straps themselves, in particular, how they are attached to the body.

3DSuit by Senztech

Senztech has three available suit formats: the under armor suit, the full body suit and the strap-based suit. All suits make use of 17 inertial sensors that measure real-time movements of each major bone segment of the body. The under armor suit has sensor pockets sewn directly into a long sleeve top and bottom creating a two piece outfit. The sensors get mounted into the pockets and cables are routed externally. The full body suit has both sensors and cables embedded into it, and therefore offers the greatest convenience. The strap-based suit has individual fixtures that are applied to each body segment offering the greatest flexibility for those who will have varying models and model sizes (Senztech, 2012). Unfortunately there is no more information available on this product.

F.A.B. by Biosyn Systems

The F.A.B. system is one of the first wireless inertial mocapping systems. It contains up to 17 sensors attachable to user selectable body segments. Sensors are mounted on elastic straps that, according the Biosyn, guarantees stable fixation (Biosyn Systems, 2012). The system does not include sensor or straps for the shoulder, shoulder movements are probably integrated in the software.

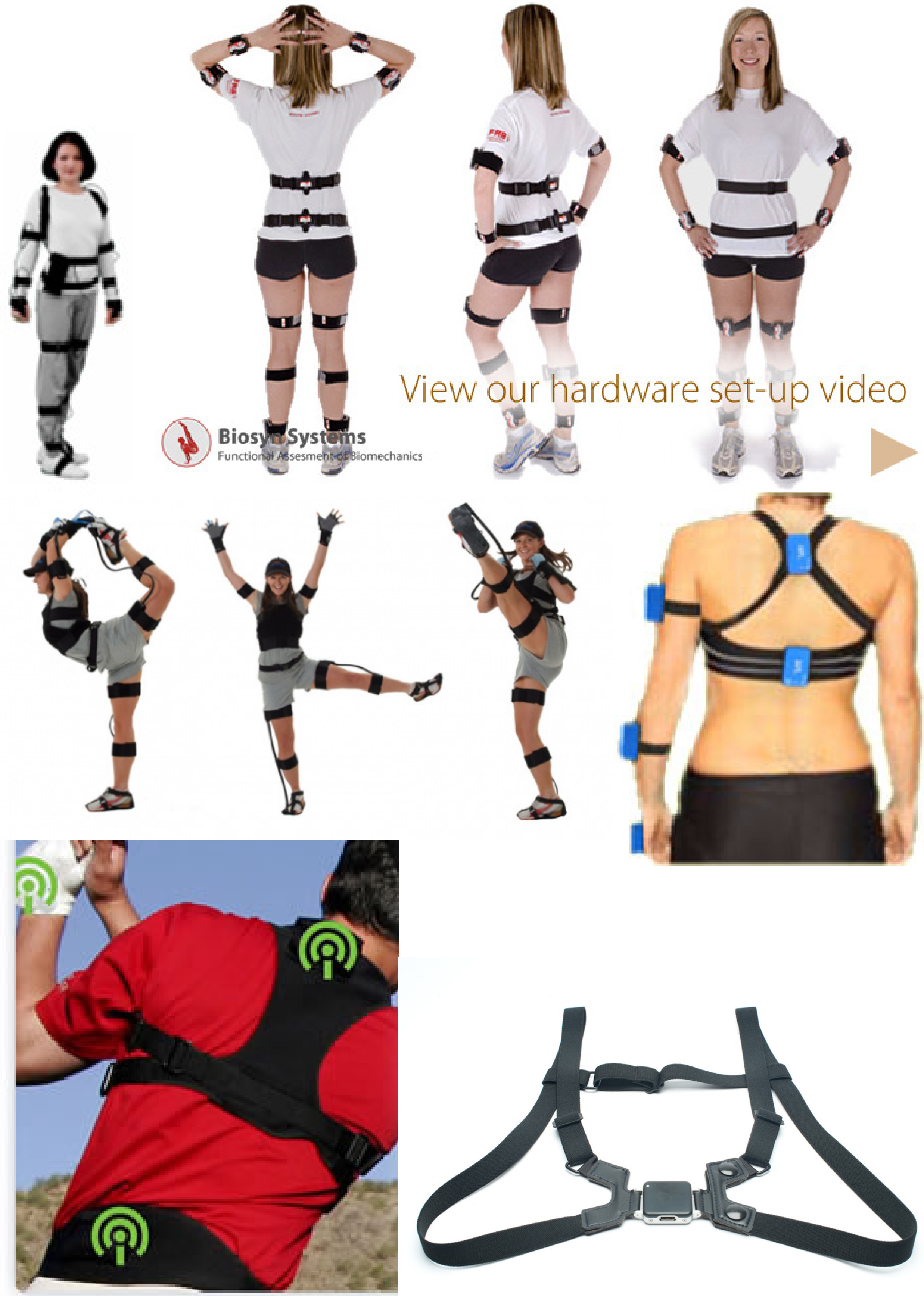

Figure 2.14 From left to right and top to bottom: 3DSuit by Senztech, F.A.B. by Biosyn Systems, ShapeWrap III by Measurand, EDDO Inertial by STT, K-Vest and APDM movement monitors.

ShapeWrap III by Measurand

The ShapeWrap III system makes use of so called ShapeTapes. These ShapeTapes conform to limbs to capture fine details of shape on a wide variety of body types. The system includes four ShapeTapes, one for each extremity and 3 separate orientation sensors to capture full body motion. The system also features a shoulder piece like MVN except it is a lot bigger and wraps around the entire chest area that is used to attach the ShapeTapes to (Measurand, 2012).

EDDO Inertial by STT

The EDDO Inertial system is a system very similar to MVN only it can use up to 24 sensors which do not include a magnetometer. The system uses some sort of strap for the upper body but the system does not use shoulder trackers like MVN so the strap does not take them into account (STT, 2012).

K-Vest

K-Vest uses wireless sensors to track motion while playing golf. It captures a player's "power signature," 3D measurements and video instantaneously. Real-time visual and auditory feedback can then be used to improve movement patterns. The system includes an upper body vest that houses a tracker on the upper back (K-Vest, 2012).

APDM movement monitors

APDM has three different systems: Sapphire, Emerald and Opal. They are all pretty much the same except for some small differences in the hardware of the inertial trackers. They are all attached to the body using the same set of straps. The system also includes an upper body strap that has the sternum tracker attached to it. But the system does not use shoulder trackers like MVN so the strap does not take them into account (APDM, 2012).

Conclusion

In conclusion, there are quite a few companies trying to do the same thing as Xsens yet none of these seem to be focusing on the shoulder as much as Xsens does. None of the systems use an extra set of trackers to capture motion from the scapula which is actually necessary to be able to track proper shoulder motion. Apparently all of the systems use some sort of algorithm to estimate the shoulder's movement using the output from the upper arm and sternum or upper back trackers. Needless to say this will never be very accurate. Xsens has an advantage here.
When comparing the MVN straps to its competition (not just the shoulder straps) it is clear that Xsens has put more time and effort in developing the straps as good as possible. Most of the competitor's straps seem to be very simple straps using Velcro or a click system to place them on the body parts. This works for the most part but after a while or after some intense movements the straps are sure to move or slide along the segment (at least this is what Xsens has experienced during the last years while using and testing the straps). Xsens has tried to minimize this by adding double track straps to certain segments where this is the biggest issue (upper arm, upper leg).

2.5 Use analysis

2.5.1 Use of straps

The straps are mainly used for research and motion analysis. The straps can be attached and tightened wherever necessary which makes them ideal for measuring only certain body parts. Also if someone has an unusual body physique they can still wear the straps. The straps are mainly being used in sports and ergonomics. They are used for measuring movement of athletes for research and improvement of their technique. In ergonomics they are used to improve products or to see how people do their jobs.
It is very important for these people that they feel free with the straps on, their movement should not be limited because this influences the results greatly. It is also important that the straps are comfortable, they should not have sharp edges or be made from some rough material that causes a lot of friction on the skin. Even though pretty much all the time people wear some clothes underneath the straps. Most of

the time they wear a short sleeve t-shirt so it is still important to keep that in mind for the straps on the arms.
For the researcher one of the most important requirements is the accuracy of the measured motion. The sensors need to measure the movement of the bones as accurate as possible. For the shoulder strap this bone is the scapula and the current shoulder piece does not do this well enough. The sensors do not stay in place.
Putting on and taking off the shoulder piece is also an important aspect. In the first place it should be easy and secondly, the position of the sensor on the body relies on how the shoulder piece is put on. If the sensor ends up in the wrong place measurements can become inaccurate.

2.5.2 Stakeholders

In order to make a list of requirements the stakeholders of MVN Biomech need to be analysed. This results in a list of functions, what the straps are used for and how they are being used and what the users want. This can then be used as a base for the list of requirements.

The stakeholders for MVN Biomech can be divided into the following groups:
- VR, training and simulation;
- Ergonomics, use analysis;
- Large test groups;
- Biomechanics;
- Rehabilitation.

An overview of all the stakeholders and their roles can be found in appendix C.

2.5.3 Functions

To finish the list of requirements the functions of the shoulder piece need to be analysed. Without knowing the actual functions of the piece it is impossible to design a new working solution.

The piece only has a few functions:
- Place and keep motion tracker in the correct position;
- Switch motion trackers quickly from person to person;
- Provides hygienic way of motion tracking (less sweat);
- Easy and quick placement of sensors on the body.

2.5.4 List of requirements

Functions and wishes of costumers have resulted in a list of requirements for the new shoulder piece. A few of the most important requirements can be found in table 2.1. The entire list of requirements can by found in appendix D.

Requirements Design	Quantification
Accuracy	
Accuracy needs to be improved	Better accuracy than current strap
Limited movement skin with respect to the bone	
Limited movement strap with respect to the clothing or skin	
Limited movement sensor with respect to the strap	
The strap must not affect movement of the user	
It should adjust to the shape of the body	
User friendliness	

Few sizes	Preferably 3 - 5
Putting on/ taking off should be fast, easy and accurate	For entire straps not longer than 10 min
It should be comfortable	
It should not restrict movement	
Wearable by physically challenged people	
Material	
Durable/maintain elasticity	

Table 2.1 List of most important requirements. The entire list can be found in appendix C.

2.5.5 Conclusion

There are a number of things that need to be taken into account when desiging a new way to measure scapular motion. First of all, a new solution needs to work better than the current solution. Measurements need to be more accurate than they are now. Secondly, a new solution needs to be user friendly which means that user should be able to put on and take off the shoulder piece quickly, easily and accurately. Lastly, a new solution needs to be comfortable for the user to wear. It should not keep the user from moving freely.

Chapter 3 - Design phase

This chapter focuses on the different concepts that have been generated for the new shoulder piece. First the old concepts that were generated by Xsens are analysed to get a sense of what works and what does not work. With that in mind, some of the most promising ideas will be described and three or four of them will be picked for further detailing and prototyping.

3.1 Earlier concepts

Xsens has come up with some ideas for a shoulder piece in the past. However, they all have their good and bad points. One of the biggest concerns was the fact that the shoulder piece needed to be one-size-fits-all. The pieces all needed to be very stretchy or adjustable in many ways. Some of the ideas might be useful now since one-size-fits-all is not a requirement anymore.

Concept 1

The first concept is similar to a backpack with straps of 10 cm wide with thin stretch material in between. The straps go around the waist and the shoulders (figure 3.1). This idea was not chosen because the combination of materials of high stretch and firm straps did not work out neatly. For better results a less elastic material would have been needed but that would cause the piece to not be one-size-fits-all. Also the large surface areas covering the body results in a lot of warmth making the subject sweat easily.

Concept 2

The second concept consists of straps that run down to the pelvic belt to avoid having very tight straps in the armpits. The straps are crossed over the middle of the back which prevents the straps from sliding of the shoulders and keeping the sensors in place. The cross point at the back is not pre-determined which makes it easier to adjust to any body size (figure 3.2). This concept was not chosen because the length of the straps make it very complicated. The positioning of the sensors is rather undetermined and putting it on is quite a hassle. It is difficult to determine what is the front and what is the back side of the piece.

Concept 3

The third concept is similar to the first but with straps of 5 cm wide and without the material in between the straps which makes it more adjustable for different body sizes (figure 3.3). This concept was first chosen because it seemed to work quite alright but has been replaced later by the current piece nonetheless when a sternum tracker was needed. Movement of the sensor was not good enough, there was some pull underneath the armpit which was quite uncomfortable.

Take note that none of the ideas described above have the sternum tracker attached to it. This is because the requirement was added later on.
A big drawback of the concepts is that they are too complicated. Lots of long loose straps does not increase user friendliness. One-size-fits-all also did not help make them less complex.

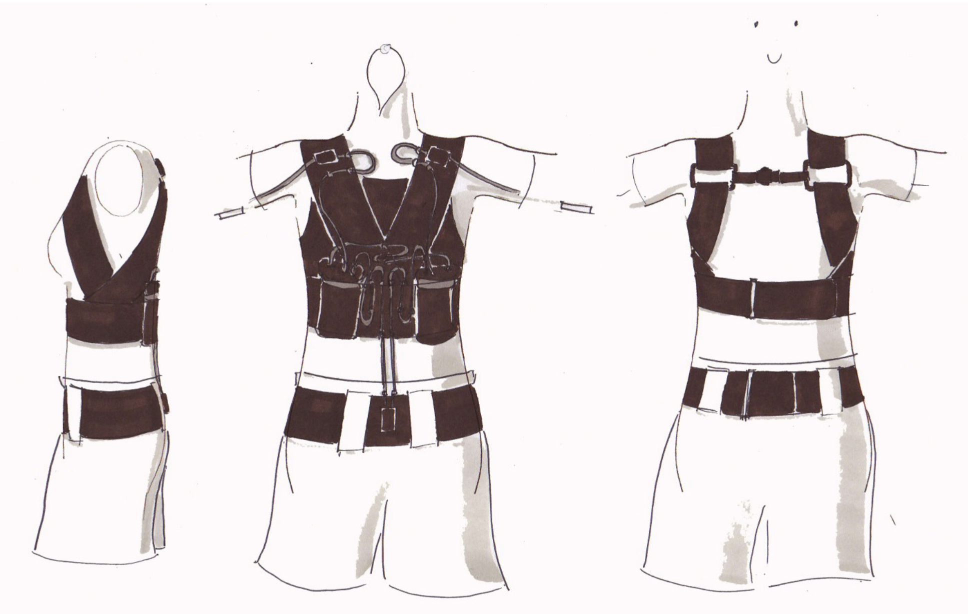

Figure 3.1 Concept 1.

Figure 3.2 Concept 2.

Figure 3.3 Concept 3.

3.2 Concept generation

To find a solution for the problems described earlier in this report, it was essential to have a few brainstorm sessions that resulted in a lot of ideas. These ideas were very simple sketches showing the basic concept of the possible new shoulder piece. Anatomy and movements of the shoulder have been kept in mind. Figure 3.4 shows a few very early ideas and notes gathered during the first few weeks. The rest of the ideas can be found in appendix E.

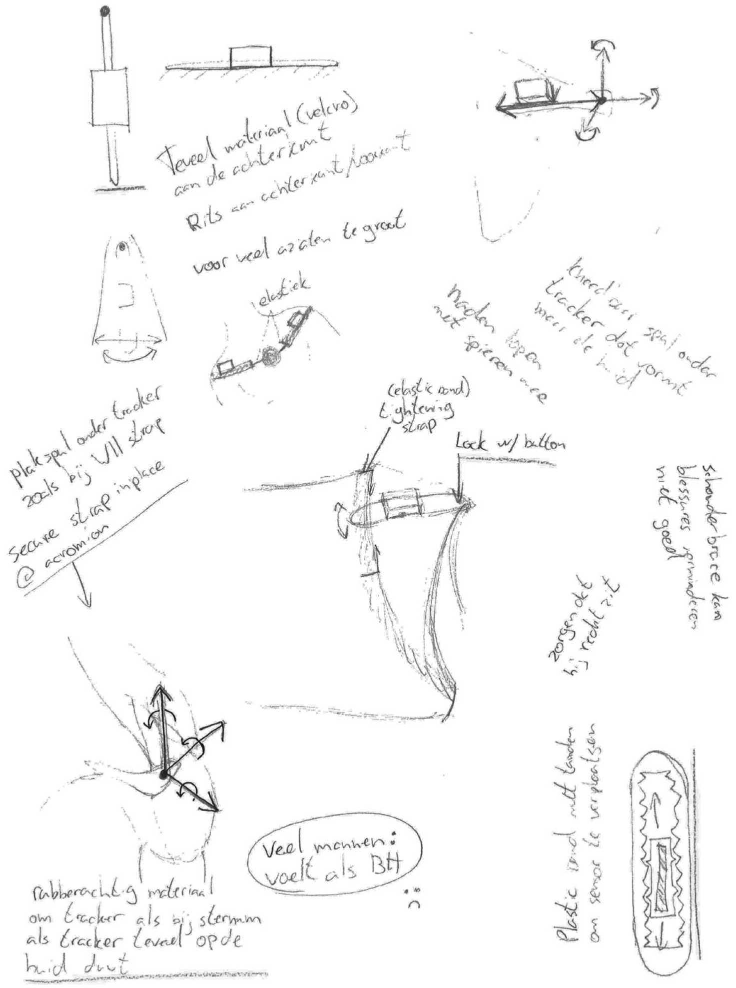

Figure 3.4 Ideas.

The ideas that were generated can be divided into five groups:
Ideas that use lycra or elastic straps at the back that pull the sensor both inwards and downwards (figure 3.5). This seemed to have potential in the first place but they are essentially loose straps like the concept in figure 3.3 but with more elasticity. Something like that needs to be avoided. That is why these ideas have not been developed any further.

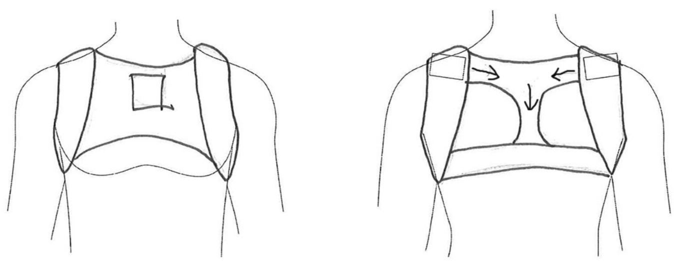

Figure 3.5 First group.

Ideas that use textile straps (PP band) to pull the sensors in place (figure 3.6). These ideas looked a lot like some concepts that have already been tried and they did not work very well and were very complicated.

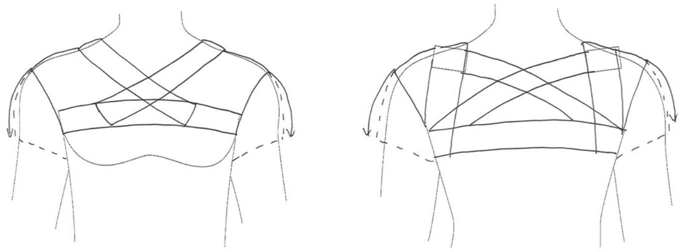

Figure 3.6 Second group.

Ideas that use lycra straps with elastic bands as reinforcements on the sides (figure 3.7). This set of ideas seemed pretty good although probably difficult to produce. Still this was something worth trying and developing some more.

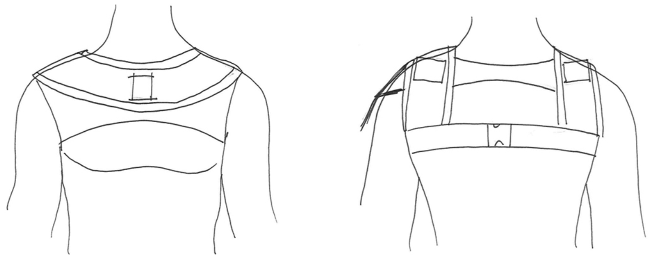

Figure 3.7 Third group.

Ideas that use tight fitting neoprene. These ideas seemed the most promising (figure 3.8). Neoprene can make the top quite tight which is thought to be a good thing.

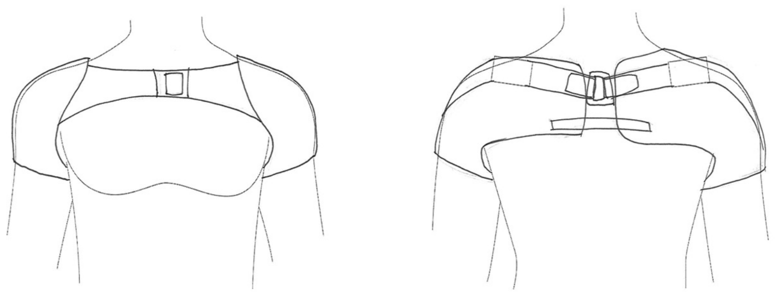

Figure 3.8 Fourth group.

Ideas that do not fit in any of these categories (figure 3.9). These last ideas did not fit into any category and were just some results from a brainstorm that did not seem to be very good.

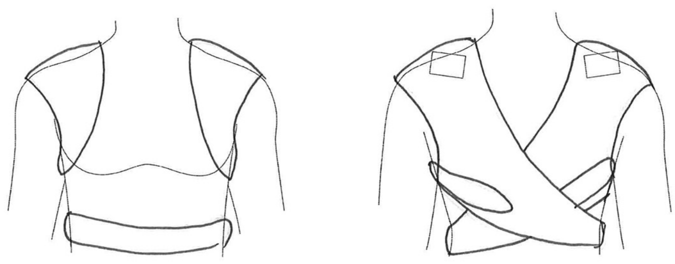

Figure 3.9 Fifth group.

3.3 Final concepts

The next part will discuss the concepts that have been chosen from the ideas that were generated. These ideas were chosen based on the three main requirements: functionality, user friendliness and freedom of movement. Functionality aims at the fact that the sensors need to be placed at the right position and that they have to track the movement of the scapula as accurate as possible, reducing the soft tissue artifact. User friendliness aims at the fact that it is clear how to put the shoulder piece on, it should not be too complicated and it should be easy to put on and take off as well. It also aims at the fact that it needs to be clear where the sensors are supposed to be placed. Misplacing the sensor should be kept to a minimum. Freedom of movement speaks for itself. The wearer should not be limited in his or her movement because this could affect the results.

Concept 1

Functionality

The first concept (figure 3.10) is a neoprene top that is based on an existing shoulder brace. Neoprene has been chosen because it is an elastic material but does not stretch as much as lycra, it sits quite tight around the body. At this moment, when high accuracy is needed for specific research, the sensors are put directly on the skin using double sided tape. If the new shoulder piece could somehow make sure that the sensors are kept tightly on the body without having to put the sensors directly on the skin than that would probably increase accuracy of the measurements. Neoprene could work.

User friendliness

The concept seems to be quite user friendly. Apart from the fact that it is pretty tight, putting it on and taking it off should be fairly easy and straight forward. It might be decided to add some Velcro straps around the sleeves so it is even easier to put on and this makes it possible to tighten the sleeves around the arms some more if necessary. The top is also wearable by women with large breasts because there is no material on the front side when using only the shoulder part. This does mean, however, that a separate strap is needed for the sternum tracker. This strap could, however, also be attached to the shoulder piece. This makes it a little bit more difficult to put on but does not seem a very big problem. The user could als choose to place the sternum tracker directly on the skin using double sided tape.

Freedom of movement

Wetsuits are also made of neoprene and in general the user can still move freely, therefore this could also work for a shoulder piece. Since the idea is based on a shoulder brace there is however a possibility that not all movements can be done so easily. If this is the case then some patches of more stretchable lycra could be added in strategic places (for example to the backside) to increase the freedom of movement. This also adds to the range of people that are able to wear it which could mean that fewer sizes are needed.

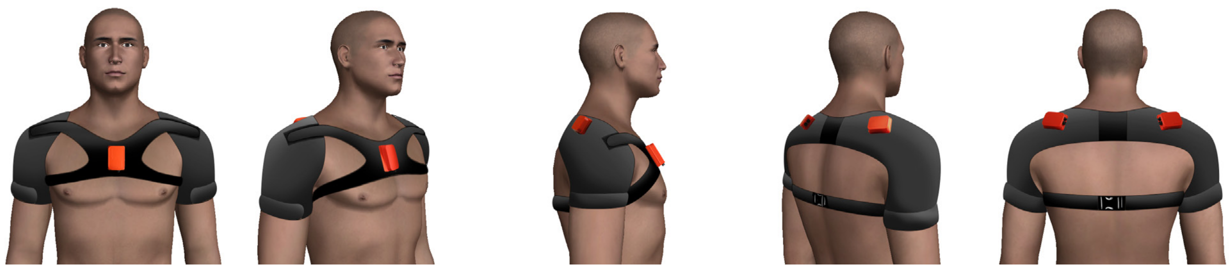

Figure 3.10 Concept 1.

Concept 2

Functionality

Concept two (figure 3.11 & 3.12) is also based on an existing shoulder brace except it is for one shoulder. Therefore this prototype consists of two parts. First one shoulder brace will be used and tested and if it seems to work then a second brace can be attached to it. The top is made of tight fitting neoprene which hopefully keeps the sensors in place. The difference with prototype 1 is the way it is put on and how it can be fastened. A strap goes underneath each arm and is secured to the front. This way there are several forces on the sensor working in different direction keeping it in place. If needed, an extra strap of lycra or neoprene can be added on top of the sensor to press it down on the skin some more.

User friendliness
In terms of user friendliness, it is probably the same as the first concept. It should not be too difficult to put on or take off. The only problem could be that people pull too hard on one side which could pull the sensor out of place. This concept could also have Velcro straps around the sleeves to tighten them if necessary.

Freedom of movement
As with concept one, this concept should not cause much problems concerning freedom of movement. If the neoprene does turn out to be too tight, then also with this concept some lycra can be added to add some more stretch.

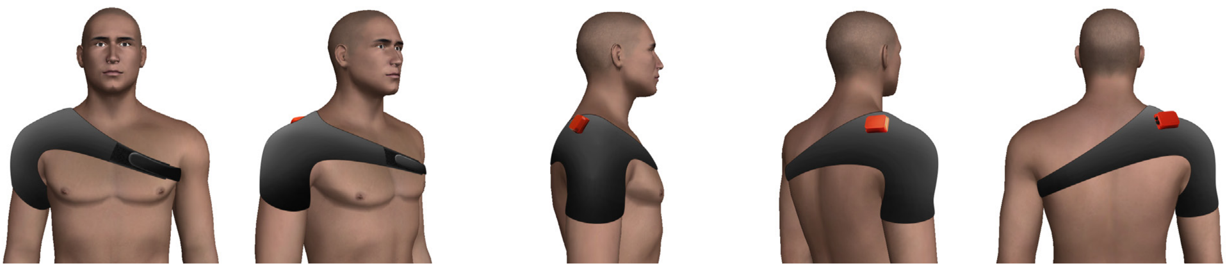

Figure 3.11 Concept 2 - single shoulder.

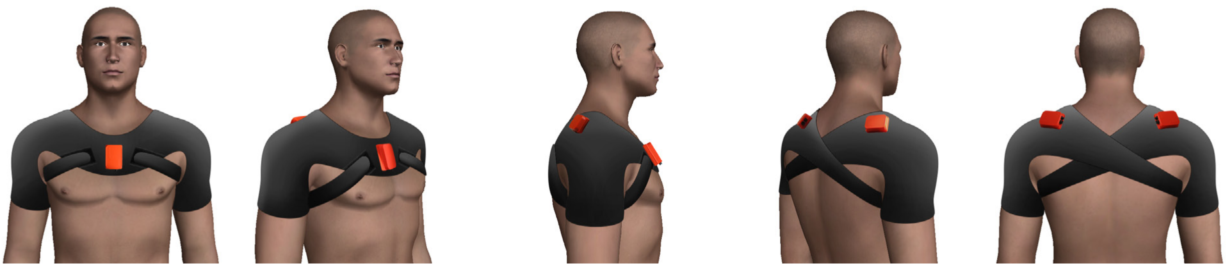

Figure 3.12 Concept 2 - double shoulder.

Concept 3

Functionality
The third concept (figure 3.13 & 3.14) is based on the fact that the sensor should be kept in the right position but also needs some space to move around to follow the movement of the scapula. To achieve this, the sensors are placed on a lycra strap that has two bands of less elastic material attached to the sides. These bands should keep the straps tightly against the body as well as the sensors in the same position, while the lycra (which is more stretchable) allows the sensor to move a little in its place. To keep everything in place some more lycra is needed to pull the straps down towards a waistband.

User friendliness
Putting the top on might be a little bit difficult because it is made of a couple of individual straps. This type of design has been tried before and it turned out that it takes quite some time to figure out how to put it on. However, this concept does not seem to be as complex as the ones tried before so it will hopefully turn out better. As for the positioning of the sensors, as long as the wearer is not too small or too big for the top this should be alright.

Freedom of movement

The elastic bands on the side of the lycra pull the top tightly onto the body. This could make it hard to move but since it does not have sleeves, moving the arms should not be a big problem. It is very similar to the current shoulder piece which is quite flexible. Also, to make it a little more female friendly, the top might cover the entire chest area so it is more comfortable and looks better on women.

Figure 3.13 Concept 3 - male.

Figure 3.14 Concept 3 - female.

Concept 4

Functionality

Concept four (figure 3.15) is more or less an upgraded version of the current shoulder piece. Since it does not have to be one-size-fits-all anymore, the Velcro strap at the back can be removed and a zipper can be added instead. The zipper can be placed on the front which makes it easier to put on if a researcher is on his own for example. By getting rid of the Velcro straps the sensors should stay in place better. The sensors are also placed on a plastic platform which lies on the spine of the scapula. Having a bigger area on the spine might make it easier to follow its movements.

User friendliness

Putting on the top should be fairly easy with a zipper in the front. It can be put on just like a normal jacket; it is just a bit tighter. Positioning the sensors should be pretty straightforward. The user cannot change anything about it so as long as the user wears the right size it should be fine.

Freedom of movement

The freedom of movement is about the same as the current shoulder piece. Apart from the plastic platforms the garment is more or less the same. However, those plastic platforms might be too big and uncomfortable and could obstruct movements in certain direction.

Figure 3.15 Concept 4.

Chapter 4 - Prototype and evaluation phase

This next chapter will discuss the next phase in the design process: making prototypes, testing and evaluating them. Prototypes will be made of the concepts described in the previous chapter. These prototypes will be tested to see if they are better than the current shoulder piece in terms of accuracy (functionality), user friendliness and freedom of movement.

4.1 Prototypes

Prototype 1

Prototype 1 is based on concept 1. The prototype is made by using an existing shoulder brace that fits both shoulders. A second separate piece can be attached to the brace using Velcro. This second piece has the sternum sensor attached to it. Lastly the sensor holders are sewn on top of the brace at the right position. The brace did not obstruct movement a lot so adding some lycra in certain places as described in paragraph 3.3 was not needed.

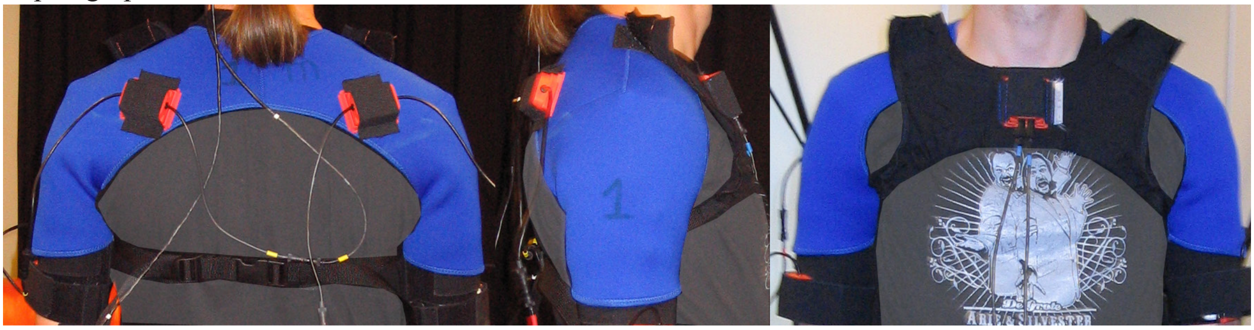

Figure 4.1 Prototype 1. Back, side, front.

Hypothesis

Because the prototype is made from neoprene it is very tight. This could compress the soft tissue around the scapula just enough for the sensor to stay in place and not be influenced as much by STA. This could, however, also restrict movements for the wearer if it is too small. An advantage of this concept is that it does not have a front side, this makes it more comfortable for women to wear. However, if a sternum tracker is required, a seperate strap can be used but users can also choose to tape the sensor on the skin (recommended for women). After some first tests it turned out that the material bulges out especially at the back while moving the arms. It is uncertain if this affects the sensors much, proper experiments should answer that question.

Prototype 2

For the first part of this prototype one of the existing shoulder braces is used. It turned out that the neoprene bulged out right where the sensor had to be placed. This was solved by sewing this bulging material to the rest of the brace. The sensor holder was sewn onto the brace and it seemed to be working pretty well.

As it seemed to work ok, the second prototype was also made. Two braces were used in the process. The straps that go around the body were cut in half in the front and another piece of neoprene was sewn on the front to attach the two braces together. This part also has the sternum tracker on it. At first Velcro was used to attach the two straps to this front part but since there is not much stretch in Velcro this really made the prototype uncomfortably tight around the chest area. The entire length of the strap needed to be retained to keep all the stretch in the material, this was accomplished by adding PP band to the ends of the neoprene straps and securing them using buckles. This way they also press down onto the sternum tracker which keeps it in place better.

Figure 4.2 Prototype 2. Back, side, front.

Hypothesis

The idea is more or less the same as prototype 1 except the design is different. It is also made of neoprene and is therefore expected to keep the sensor in place. As far as functionality, it seems to work quite well but experiments are needed to be sure. A problem that might occur is that the sternum tracker is being pushed out of place by the straps.

Prototype 3

Prototype 3 will not entirely be made. It is based on concept 3 and after a talk with an expert in sewing and making patterns it was clear that realisation would take up a lot of time and would be quite difficult. Getting the curve in the front part of the strap would be difficult because elastic bands are not naturally curved. She also was not sure if it would work without the right materials. Because time and expertise were not sufficiently available, the decision was made to make a sub-prototype to test the questionable principle of the concept. Two elastic bands are attached to a strip of lycra of about 7 cm wide and some Velcro is attached to the ends of the strip so it can be wrapped around the waist to see what happens to the sensor. A sensor holder is sewn onto the lycra at an angle similar to how it would have been on the actual prototype.

Figure 4.3 Prototype 3.

Hypothesis

By wrapping the strap tightly around the waist it was immediately clear that it did not work as expected. The elastic bands pulled together which folded the lycra causing the sensor to hang loosely on the lycra. Pulling it tightly over the shoulder did not make much of a difference especially when moving the arm upwards, the elastic bands did not seem to do much. Perhaps pulling it tightly in all directions would help but realizing this in the prototype would take up too much time and, as stated before, the needed curve in the strap is difficult to make. By sewing a plastic strip underneath the sensor holder, the problem of the sensor hanging was more or less solved but the elastic bands were not very functional anymore. The expectation is that the idea probably will not work or will make the strap too complex. It is also necessary to pull the strap very tight which makes it uncomfortable to wear for a long time and might make large movements of the arms difficult. Another point is that it needs to be adjustable. The fact that there are multiple sizes does not mean there is a size for everyone, a little bit of adjustment is still necessary. The problem with this concept is that if there is only one way of adjusting it, the sensors can be pulled out of place so another adjustment point has to be added. This makes it even more complex and inexperienced users can pull the sensors out of place even more. This prototype will be discarded because it probably does not function and because of its complexity.

Prototype 4

To make prototype 4 the current shoulder piece has been used with some adjustments. The Velcro has been removed and replaced with lycra and the shoulder sensors have not been added. Two types of plastic platforms have been put into pockets. On the left a long plastic platform following the spine of the scapula is inserted in a pocket and on the right a plastic cross has been inserted in a pocket.

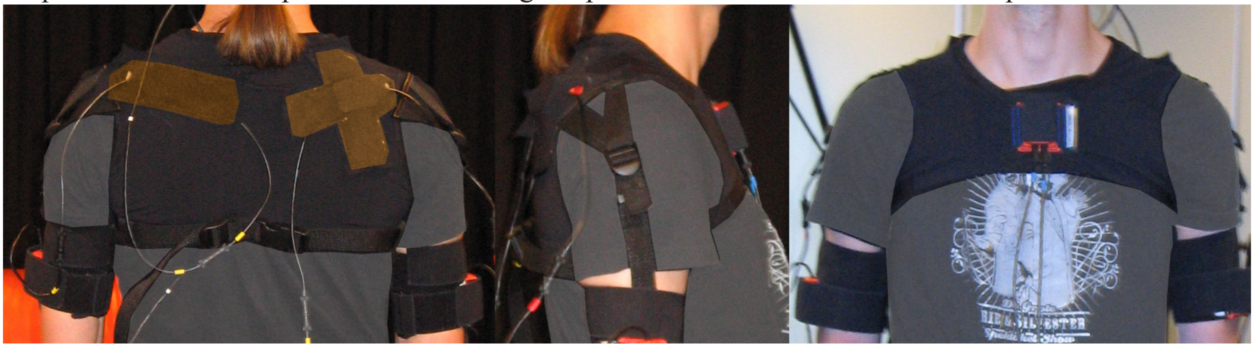

Figure 4.4 Prototype 4. Back, side, front.

Hypothesis

As observed in the previous prototype, adding plastic straps underneath the sensors could make them more stable. Having a bigger contact area against the spine of the scapula could help following its movement. The cross has a second plastic strap that acts as another stabilizer that prevents rotation along the sensor's longitudinal axis. A point of concern is the fact that it might be too rigid and could obstruct movement, but prototype 3 has shown that this might not be such a big problem after all. Also after a first test it did not seem a problem at all. But whether they actually do something and improve the accuracy of the measurements is not clear, some proper experiments are needed.

4.2 Experiments

To get to know whether the chosen concepts are better than the current shoulder piece, it is necessary to do some experiments with the prototypes.
Two experiments will be performed. During the first experiment two variables will be investigated to determine if the new concepts work better: functionality and freedom of movement. Functionality aims at the most important function of the shoulder piece: keeping the shoulder tracker in place and accurately measure movement of the scapula. And freedom of movement means that users should be able to perform all kinds of movements without being obstructed by the strap.
During the second experiment the user friendliness will be tested. User friendliness aims mainly at putting on and taking off the piece easily and correctly without putting the sensors in the wrong place.

4.2.1 First experiment

Six participants are needed for the experiment, preferably three men and three women of about the same size but with different postures. The size depends on the size of the prototypes, which are medium and the postures should preferably be skinny, big and muscled or athletic. The participants should also be healthy adults; Xsens employees, students or other volunteers.
The experiments will be performed in the Vicon lab using the MVN system, prototypes, a laptop, double sided tape, a video camera and a normal camera. Participants will be asked to perform a number of movements with the arms: abduction (figure 2.10), flexion (figure 2.9) and shrugs (figure 2.11 - elevation-depression). This will be done with the sensors taped on the skin, with the current shoulder piece

and with the prototypes. Before the real tests the participants will get some time to move around freely so they can get used to the shoulder piece and judge the freedom of movement of the prototypes. This is also a good time to see if the sensors stay in the same place or if anything needs to be adjusted.
Every participant will be photographed in their initial pose (N-pose), with their arms in the end pose and in the N-pose again after all movements are done to see if the sensors are still in the same place and so it can be compared to the MVN Studio results for a visual reference. The protocol for the experiment can be found in appendix F.

The tests will result in many graphs in MVN Studio, observations and opinions of the subjects. The only data that is needed from MVN Studio are the three joint orientations (X, Y and Z) from the left and right C7 joints, left and right shoulder joints (figure 4.5) and the X, Y and Z positions of the left and right hands. The data can be plotted in graphs using Microsoft Excel and can very easily be compared to one another. The data from the first test with the sensors on the skin serves as a reference; this is considered the golden standard. The data from the second test with the current shoulder piece serves as a second reference. By comparing the graphs of the prototypes to the two reference graphs, a conclusion can be made as to whether or not the prototypes are better than the current shoulder piece. By comparing both the C7 and the shoulder joint in all three directions a more detailed conclusion can be drawn, perhaps one of the prototypes works very well in one or two directions but performs bad in the other. Another interesting thing to compare is the positions of the hands during movements when the hands touch. If measurements are done correctly than the hands of the 3D model should touch at all times. This can not only be seen but also calculated more precisely. By taking the root mean square of the X, Y and Z positions of both hands and subtracting them, the results should be close the zero at all times. If this is not the case, than the prototype does not work correctly while doing certain movements.

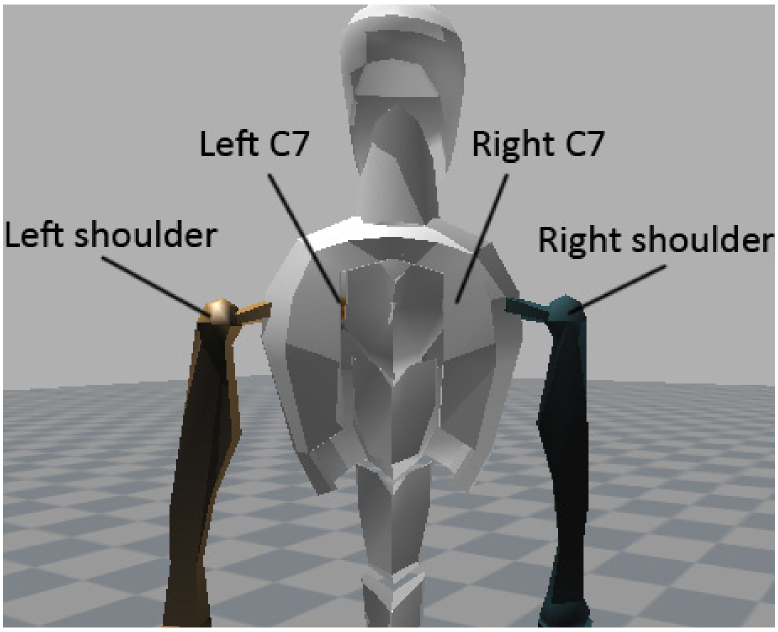

Figure 4.5 Back view of the MVN model showing the four joints. The C7 joints are located inside the “thorax”.

4.2.2 Second experiment

For the second experiment three MVN Straps experts and three non-experts are needed. They are asked to help a subject (probably me or another volunteer) put the prototypes on and take them off. Afterwards they will be asked what they thought of the prototypes in terms of user friendliness.

Observing the people should give a good view on how the prototypes function in terms of user friendliness. Asking their opinions will enhance this view into more detail.

4.3 Results

Unfortunately only 3 test persons were found to test the prototypes. The reason for this is because no women could be found who would fit the prototypes, the prototypes were too big. Therefore they were only tested on three men, more would have been better for the results but a lack of time prevented doing more tests as well. Also one person was probably a little bit too small for the prototypes and another was too big.
All the obtained graphs were compared to the two reference graphs on both shape and scale. Shape is the most important of the two. Scale is less important but does need to be taken into account. Every graph was given a score of -1, 0 or 1 if it was worse, the same or better than the current shoulder piece respectively, looking at shape in the first place and also scale. Examples of this process follow below. By adding the scores together a conclusion can be made as to whether or not a prototype is better. It is also possible to see in which directions and for which movements a prototype works better. This could perhaps result in a combination of prototypes that works perfectly for everything.

Example: worse than current solution

Figure 4.6 shows the graphs for the skin-taped sensors (blue), the current shoulder piece (red) and the first prototype (green) for the left C7 segment while the subject performed the abduction movement five times. The blue line represents the "golden standard", this is the most accurate result that can be obtained with the current system. As can be seen each repetition consists of two peaks, a big one with a difference between the minimum and maximum (range) of about 15° and a small one with a range of about 2°. The red line however has a much larger first peak with a range of about 25°. This means there is already a difference of 10° between the reference and the current shoulder piece. The green peak shows an even larger first peak with a range of about 35° and it barely has a second small peak. This example clearly shows that the prototype does not even remotely come close to the reference and it is even worse than the current shoulder piece. The prototype would get a score of -1 for this particular situation.

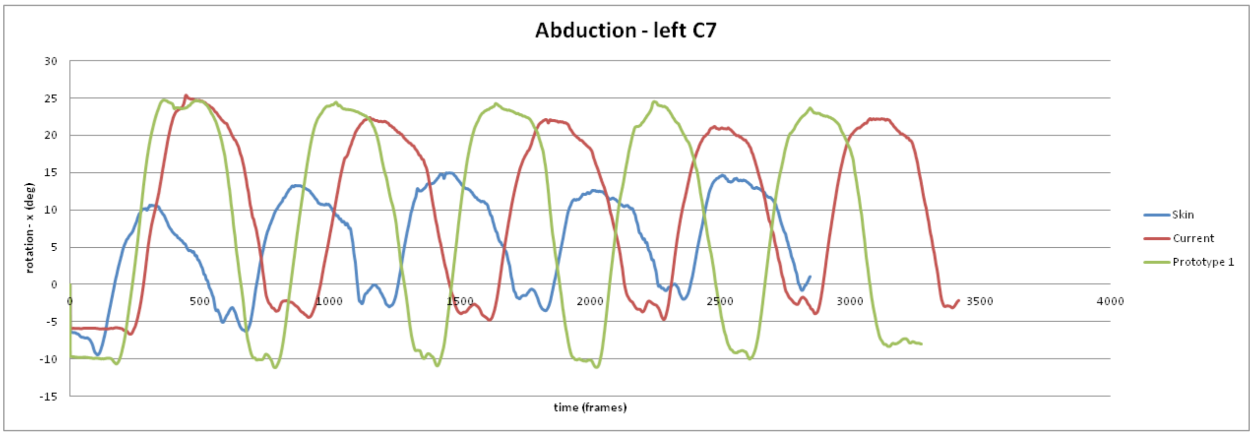

Figure 4.6 Example that shows the graphs for the skin-taped, current strap and the first prototype solutions.

Example: same as current solution

Figure 4.7 shows the graphs for the skin-taped sensors (blue), the current shoulder piece (red) and the second prototype (purple) for the left shoulder segment while the subject performed the abduction movement five times. Again the blue line represents the "golden standard". In this case it is clear that there is not a big difference between any of the graphs. The peaks are all more or less the same. The small difference in height is more likely caused by the movement being done slighty different each time rather than the prototype not functioning well. In this case there is no real difference between the current shoulder piece and the prototype and is therefore scored as 0.

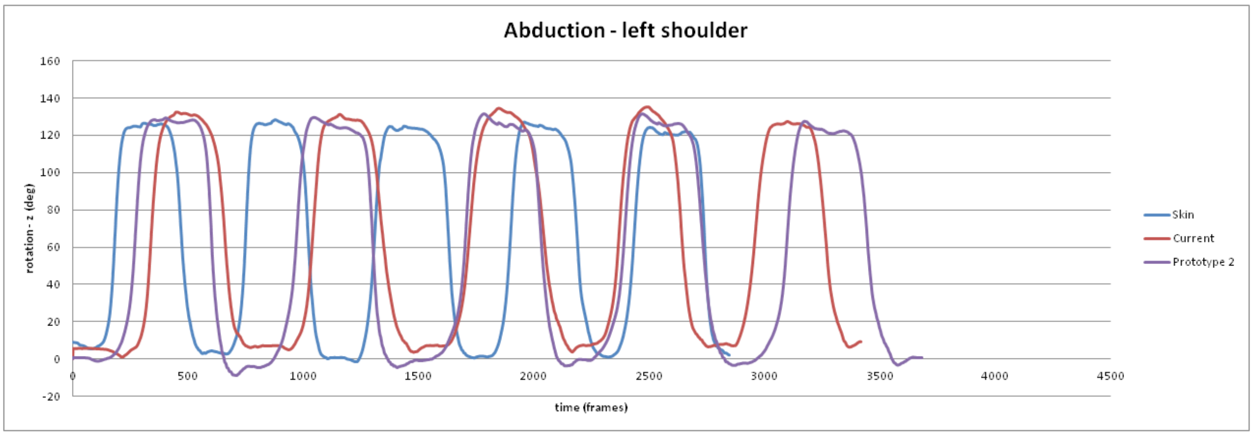

Figure 4.7 Example that shows the graphs for the skin-taped, current strap and the second prototype solutions.

Example: better than current solution

Figure 4.8 shows the graphs for the skin-taped sensors (blue), the current shoulder piece (red) and the third prototype (light blue) for the left C7 segment while the subject performed the shrugs movement five times. Again the blue line represents the “golden standard”. In this case the peaks show a range of about 17° while the red line shows a range of about 23°. The light blue line also shows a range of about 17°. This is better then the result from the current solution and it is even close to the skin-taped solution. This means the prototype gets a score of 1.

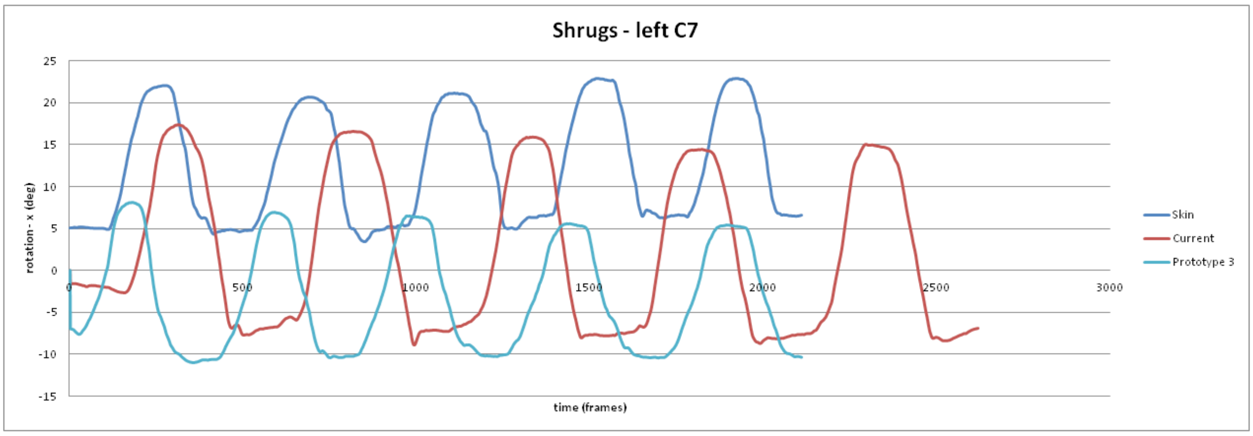

Figure 4.8 Example that shows the graphs for the skin-taped, current strap and the third prototype solutions.

Prototype 1

Prototype 1 seems to be the worst of them all, it gets a negative score for every participant. It is, however, the most comfortable according to the participants. One person said he had some trouble with the abduction movement, that is probably because the back was not elastic enough. Another said it was a little bit tight around the arms, but he was generally just too big for the prototype. The reason it does not work so well is probably because it does not stretch enough, instead the material bulges. This is particularly true for the back side, this moves the sensors in a way that is not desired.
As for user friendliness, people immediatly know how to put it on. The only downside is that most people do not realize the sternum part can be taken off to make it easier to put on or take off the piece. They also do not realize they can adjust the position of the tracker this way.

	Prototype 1													Total
	lC7 x	lC7 y	lC7 z	rC7 x	rC7 y	rC7 z	lSho x	lSho y	lSho z	rSho x	rSho y	rSho z	touch	
Bjorn - abduction	-1	0	1	1	-1	0	-1	-1	0	-1	0	-1		-4
Bjorn - flexion	1	-1	-1	0	1	-1	1	0	-1	-1	0	-1		-3
Bjorn - shrugs	1	-1	0	0	-1	0	0	0	-1	1	-1	-1		-3
Bjorn - handtouch													0	0
SubTotal	1	-2	0	1	-1	-1	0	-1	-2	-1	-1	-3	0	-10
	Prototype 1													Total
	lC7 x	lC7 y	lC7 z	rC7 x	rC7 y	rC7 z	lSho x	lSho y	lSho z	rSho x	rSho y	rSho z	touch	
Damien - abduction	-1	-1	1	0	0	1	0	0	0	-1	-1	0		-2
Damien - flexion	0	0	-1	0	0	1	0	0	0	-1	0	0		-1
Damien - shrugs	0	1	0	1	-1	-1	0	0	0	1	-1	-1		-1
Damien - handtouch													-1	-1
SubTotal	-1	0	0	1	-1	1	0	0	0	-1	-2	-1	-1	-5
	Prototype 1													Total
	lC7 x	lC7 y	lC7 z	rC7 x	rC7 y	rC7 z	lSho x	lSho y	lSho z	rSho x	rSho y	rSho z	touch	
Job - abduction	-1	-1	0	1	0	0	0	1	0	-1	0	0		-1
Job - flexion	0	0	0	1	-1	0	1	1	0	-1	0	0		1
Job - shrugs	1	0	-1	1	0	0	-1	0	-1	-1	0	0		-2
Job - handtouch													1	1
SubTotal	0	-1	-1	3	-1	0	0	2	-1	-3	0	0	1	-1
Total	0	-3	-1	5	-3	0	0	1	-3	-5	-3	-4	0	-16

Table 4.1 Results from prototype 1. The columns show the different joint angles, the rows show the movements per participant.

Prototype 2

Prototype 2 does not perform too well either. It is also quite comfortable and does not show a lot of problems when moving the arms, but the results from the experiment also show some negative scores. It came out positive for only one person. Comparing the pictures that have been taken during the experiments also shows that he fit the prototype the best, it was a little bit too small for the other two participants which could be one reason why it scored so badly. Another reason could be that the prototype itself was badly made. The pictures show that for every participant the left shoulder sensor is not in the correct posititon, it was too low (figure 4.2). Also, the straps on the front push away the sternum sensor (figure 4.9). Perhaps by improving the prototype and adjusting some parts it could work better.
User friendliness of this prototype was not so good. People who already had some experience with the straps knew pretty much right away how to put it on but inexperienced people had some problems and needed some help.

Figure 4.9 The sternum sensor is being pushed aside by the straps.

	Prototype 2													Total
	lC7 x	lC7 y	lC7 z	rC7 x	rC7 y	rC7 z	lSho x	lSho y	lSho z	rSho x	rSho y	rSho z	touch	
Bjorn - abduction	-1	1	0	1	1	1	-1	-1	0	-1	0	-1		-1
Bjorn - flexion	0	0	-1	1	1	-1	1	0	0	0	-1	-1		-1
Bjorn - shrugs	-1	-1	-1	0	0	0	0	-1	-1	1	-1	-1		-6
Bjorn - handtouch													0	0
SubTotal	-2	0	-2	2	2	0	0	-2	-1	0	-2	-3	0	-8
	Prototype 2													Total
	lC7 x	lC7 y	lC7 z	rC7 x	rC7 y	rC7 z	lSho x	lSho y	lSho z	rSho x	rSho y	rSho z	touch	
Damien - abduction	0	-1	1	1	0	0	0	1	1	0	0	1		4
Damien - flexion	-1	0	0	-1	1	0	0	1	0	0	0	-1		-1
Damien - shrugs	0	1	-1	1	-1	-1	0	0	0	0	-1	1		-1
Damien - handtouch													-1	-1
SubTotal	-1	0	0	1	0	-1	0	2	1	0	-1	1	-1	1
	Prototype 2													Total
	lC7 x	lC7 y	lC7 z	rC7 x	rC7 y	rC7 z	lSho x	lSho y	lSho z	rSho x	rSho y	rSho z	touch	
Job - abduction	-1	-1	0	-1	1	0	0	1	0	0	0	0		-1
Job - flexion	-1	-1	0	1	0	0	0	1	0	1	-1	0		0
Job - shrugs	1	0	0	0	0	-1	1	1	0	-1	0	0		1
Job - handtouch													0	0
SubTotal	-1	-2	0	0	1	-1	1	3	0	0	-1	0	0	0
Total	-4	-2	-2	3	3	-2	1	3	0	0	-4	-2	-1	-7

Table 4.2 Results from prototype 2.

Prototype 3

This prototype is actually prototype 4 but since prototype 3 has not been made, it has been renamed. It also consists of two parts: left and right. Left has the single plastic platform, right has the cross shaped plastic platform. This prototype works better than the other two, especially the right side. Apparently the platforms give the sensors a little bit more stability. But since the rest of the top is more or less the same as the current shoulder piece it is not very comfortable. It is better than the current shoulder piece because it does not have the Velcro but it still pulls underneath the armpits which is annoying if it is worn for a long time. The participants did not say anything about the platforms, they did not find them uncomfortable, they did not even notice they were there. Putting the top on was a bit difficult, but that was expected. The prototype did not have a zipper so it had to be put on over the head like a normal shirt and since it was quite tight this was not so easy. But if it would have a zipper this would not be a problem.

User friendliness of this prototype was quite good. The fact that it looks a lot like the current shoulder piece may have made it easier for the people at Xsens because most of them already knew how to put that on. Not having the Velcro on the backside made it even easier to put on straight, there was less room for errors.

	Prototype 3 left						Total		Prototype 3 right						Total
	lC7 x	lC7 y	lC7 z	lSho x	lSho y	lSho z		touch	rC7 x	rC7 y	rC7 z	rSho x	rSho y	rSho z	
Bjorn - abduction	-1	1	1	0	-1	0	0		1	1	0	0	-1	0	1
Bjorn - flexion	-1	-1	0	0	-1	0	-3		1	-1	1	0	0	0	1
Bjorn - shrugs	0	-1	-1	0	-1	-1	-4		1	0	0	1	-1	-1	0
Bjorn - handtouch								0							
SubTotal	-2	-1	0	0	-3	-1	-7	0	3	0	1	1	-2	-1	2
	Prototype 3 left						Total		Prototype 3 right						Total
	lC7 x	lC7 y	lC7 z	lSho x	lSho y	lSho z		touch	rC7 x	rC7 y	rC7 z	rSho x	rSho y	rSho z	
Damien - abduction	0	-1	1	0	1	1	2		0	1	0	0	0	1	2
Damien - flexion	1	-1	1	0	0	0	1		1	-1	1	0	0	1	2
Damien - shrugs	0	1	-1	0	0	0	0		1	-1	0	0	-1	0	-1
Damien - handtouch								-1							
SubTotal	1	-1	1	0	1	1	3	-1	2	-1	1	0	-1	2	3
	Prototype 3 left						Total		Prototype 3 right						Total
	lC7 x	lC7 y	lC7 z	lSho x	lSho y	lSho z		touch	rC7 x	rC7 y	rC7 z	rSho x	rSho y	rSho z	
Job - abduction	1	-1	0	0	0	-1	-1		0	-1	-1	1	0	0	-1
Job - flexion	1	-1	1	0	1	0	2		1	1	0	1	0	0	3
Job - shrugs	1	1	1	-1	1	1	4		1	1	0	-1	0	0	1
Job - handtouch								0							
SubTotal	3	-1	2	-1	2	0	5	0	2	1	-1	1	0	0	3
Total	2	-3	3	-1	0	0	1	-1	7	0	1	2	-3	1	8

Table 4.3 Results from prototype 3.

Errors

Unfortunately, doing these experiments with different people is very difficult. Each person performed the movements slightly different and even each movement from every individual was different. Comparing the graphs was not an easy task because of this. Not only that but also calibrations could have been done slightly different each time, or the sensors could have been in the wrong place which is a serious flaw in the prototype. This could have made the measurements less accurate. Also the fact that people were too small or too big for the prototypes could have influenced the tests. A lot of variable were present that are very difficult to control because of the fact that humans are involved and everyone is different. To get more accurate results a lot more tests should have been done, but there was simply no time to do all that.

Chapter 5 - Discussion and recommendations

In this project a new shoulder strap for the MVN Straps had to be realized. The shoulder strap contains the shoulder sensors that are supposed to track the motions of the scapulas. However the current shoulder piece does not function so well. This is partly because of the so called soft tissue artifact and partly because of the complexity of the piece, the complexity of the shoulder girdle and the way everything moves in that area of the body. Especially the scapula is very difficult to track because it is covered in muscles and moves underneath the skin unlike for example the upper arm which does get affected by STA but does not move or slide underneath the skin. Apart from accurately tracking the scapula, the new shoulder piece should also be user friendly and it should allow the user to move freely.

In the first and second chapter the problem has been thoroughly described. With an understanding of the problem one thing could already be said to optimize shoulder tracking: one-size-fits-all is not a good idea. It is highly recommended to develop a shoulder piece in several sizes (3 to 5 depending on the chosen concept). With this in mind some ideas could be generated that would hopefully work properly (Chapter 3). The most promising ideas have been elaborated into prototypes. Unfortunately there was only time to create three prototypes. Two of these were completely new and involved using neoprene instead of lycra. Neoprene was thought to be a tight fitting material which would keep the sensor in the right position. The third prototype was similar to the current shoulder piece except it has some pockets with plastic platforms that were expected to give some more stability to the sensors.

Chapter 4 described the experiments that were performed to test the different prototypes. During the experiments a reference for validation of the prototypes was needed. Currently when accurate measurements are needed the sensors are attached directly on the skin using double-sided tape. This method was assumed to give the best possible results which is why it was used as a reference. Unfortunately the results showed quite some inconsistency. There are a number of reasons that could have caused these inconsistencies. First of all it is very difficult to have each subject perform exactly the same movements every single time. Secondly the calibrations could have been done incorrectly, it is possible that a subject did not perform the N-pose correctly every time. Thirdly the sensors can be misplaced, which is a flaw in the prototypes or, in the case of the skin-taped sensors, this is caused by the one performing the experiments. Lastly the subjects did not fit the prototypes very well. Since they are not one-size-fits-all anymore several sizes were needed but there was only time to make one size for each prototype. This made searching for subjects more difficult and it was clear that during the experiments one subject was too big and another was too small for the prototypes. This influenced the results, but it is also good to know that having the right size is very important.

According to the results from the tests prototype 1 does not function very well. The results show no improvement in accuracy. The main reason for this is that the material bulges when the arms are moved. The material pushes against the sensors causing them to move unrelated to the shoulder movement. It is however considered to be the user friendliest and most comfortable. All of the subjects thought it felt better than the current shoulder strap and when inexperienced people tried to put it on by themselves they immediately knew how to. Perhaps if the part that bulges out were to be replaced by lycra, the strap would stay more tightly onto the body and the material would not be able to push away the sensors.

The second prototype is not much better than the first one. However with some adjustments it might work better and may be worth to try in the future. First of all, the left sensor was placed incorrectly on the prototype, it was too low. This was not noticed untill the experiments and it may have influenced the results. Secondly, when moving the arms, the material clearly bulged out in the same place every time. To fix this the excess material was taken and sewn flat onto the rest of the material. This resulted in a small bump on which the sensor had to be placed. This was not ideal and should be fixed in a future prototype. This was not done in this prototype because cutting it away would have been a waste of the brace if something had gone wrong and there were no extra braces. Thirdly, the way the straps have to be fastened is not so easy, buckles should be used and perhaps they should also be placed somewhere else because right now the straps are pushing away the sternum sensor. Perhaps the sternum sensor can be placed underneath the neoprene or on a tougher material like on the current shoulder piece. This may give it some more stability. As far as comfort this prototype scored ok, just like the first prototype, most subjects found it to be more comfortable than the current shoulder piece. There was only the issue with the biggest subject who found that it was too tight around his arms. This could easily be fixed by cutting the sleeves in two and adding a Velcro strap so the sleeves can be manually tightened. This also goes for the first prototype. For user friendliness it scored lower, especially inexperienced people did not know immediately what to do with the straps but once they knew they found it very logical.

The third prototype is the most promising and because it is pretty much the current shoulder piece with a couple of adjustments it is also the easiest and probably cheapest solution to implement for Xsens. The right solution, the one with the cross-shaped platforms seems to work the best. The plastic platform around the sensor gives it some more stability in several directions and the fact that there is no Velcro has also improved it. It is recommended to perform some more tests with this prototype to be sure it works better. It might even be better to create two prototypes, one with the cross on both sides and one with the single platform on both sides. Also adding a zipper on the front will improve user friendliness. For a prototype it worked fine without one, but a zipper is highly recommended especially when it is used on for example old or handicapped people.

In conclusion, the second and third prototypes could be improved or adjusted as described above and tested again. Perhaps the second prototype is not so bad. However if this turns out to work quite well, there is something to keep in mind. It is known that people can get allergic reactions from neoprene when it touches their skin (Stern et al., 1998), a warning is required and perhaps even a different material should be considered. There are a couple of other materials available that have the same characteristics as neoprene but do not cause allergic reactions. Neogreene (Greensmart, 2012) is one alternative that is also better for the environment. A second alternative is Drytex (Donjoy, 2012). The advantage is that it is more comfortable to wear and is also breathable and therefore less hot. However, currently the fabric is only exclusively produced for a company called DonJoy. A third alternative is Thermocline (Fourth element, 2012) which is specially designed for people who cannot wear neoprene wetsuits because of allergies.

Literature

Animazoo, http://www.animazoo.com

APDM, http://www.apdm.com

Biosyn Systems, http://www.biosynsystems.net

Bray, J. (1958). *Prosthetic principles upper extremity amputations.* University of California, Los Angeles: Prosthetics-Orthotics Education Program – Division of Orthopedic Surgery

Cao, L., Masuda, T., Morita, S. (2007). *Compensation for the Effect of Soft Tissue Artifact on Humeral Axial Rotation Angle.* Department of Rehabilitation Medicine, School of Biomedical Science; Tokyo Medical and Dental University, Tokyo, Japan

Cutti, A.G. (2006). *Motion analysis assessment of upper extremity motor ability.* Faculty of Engineering, University of Bologna, Italy

Della Croce, U. (2006). *Soft tissue artifacts in human movement analysis.* Department of Biomedical Sciences; University of Sassari, Sassari, Italy

Dined, http://dined.io.tudelft.nl/dined/

Donjoy, http://www.donjoy.eu

Fouth element, http://www.fourthelement.com

Garofalo, P., Xsens, Enschede*

Healthpages, http://www.healthpages.org

K-Vest, http://www.k-vest.com

Matsui, K., Shimada, K., Andrew, P.D. (2005). *Deviation of skin marker from bone target during movement of the scapula.* Department of Physical Therapy; Ibaraki Prefectural University of Health Sciences, Ibaraki, Japan

Measurand, http://www.motion-capture-system.com

Metamotion, http://www.metamotion.com

Monaghan, C., Xsens, Enschede*

Nolli, G., Xsens, Enschede*

Greensmart, http://www.greensmart.biz

Organic Motion, http://www.organicmotion.com

Platzer, W. (2003). *Sesam Atlas van de anatomie.* 20e druk. Baarn: SESAM/HBuitgevers; ISBN: 90 5574 242 2

Roetenberg, D., Xsens, Enschede*

Roetenberg, D. (2006). *Inertial and Magnetic Sensing of Human Motion.* University of Twente; ISBN-10: 90-9020620-5

Senztech, http://www.senztech.cc

Shoulderdoc, http://www.shoulderdoc.co.uk

Stern, E.B., Callinan, N., Hank, M., Lewis, E.J., Schousboe, J.T., Ytterberg, S.R. (1998). *Neoprene Splinting: Dermatological Issues.* The American Journal of Occupational Therapy.

STT, http://www.stt.es

Tan, K., Xsens, Enschede*

Zygotebody, http://www.zygotebody.com

***Human resources**

Koen Tan – Koen is a test engineer at Xsens Technologies BV. His main job is to test the software and hardware created by Xsens to help further development of the products.

Pietro Garofalo – Pietro is technical product manager in the movement science area at Xsens Technologies BV. He has got a biomechanical background and has studied the shoulder to great extent.

Daniel Roetenberg – Daniel is lead engineer and has a biomechanical background.

Colleen Monaghan – Colleen is product manager for MVN Biomech. She has got a biomechanical background and has helped in the development of the MVN Straps.

Giovanni Nolli – Giovanni is a MVN Biomech product specialist.

Appendices

Solutions for positioning inertia measurement units for motion tracking

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Bachelor assignment at
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Contents

A - Inertial measurement unit

Inertial measurement units or IMUs are sensors that can measure orientation (roll, pitch and yaw). They include three types of 3D sensors that all work together to accurately measure the orientation of the IMU. The sensors are an accelerometer, a gyroscope and a magnetometer.

Accelerometer

This sensor measures, as the name states, accelerations. It uses the earth's gravitational force to determine its orientation. The earth's gravitational force can be seen as a downwards acceleration of about 9,8 m/s^2 which is always present, everywhere on earth. If the IMU is in a neutral position i.e. it is lying flat on a tabletop, then only the accelerometer orientated in the Z-direction (vertical direction) will register an acceleration. If the IMU is rotated around the X- or Y-axis (horizontal axis) then the two other accelerometer orientated in the X- and Y-direction will measure an acceleration. The resultant acceleration of these three measurements can be calculated and should always be pointing straight down (negative Z-axis) because of the direction of the earth's gravity. The orientation of the IMU is now easily calculable by calculating the angles between the resultant and the X-, Y- and Z-axis.
Using only accelerometers to measure orientation is not enough for motion capture technology. People will be moving around, therefore creating more accelerations in different directions which are being measured by the sensors resulting in a different resultant and thus resulting in inaccurate orientation of the IMUs. Also these sensors are not able to measure acceleration around the vertical axis. Therefore a 3D gyroscope and a 3D magnetometer are added.

Gyroscope

Gyroscopes measure angular motion. In case of a 3D gyroscope it measures angular velocity in all three axis. IMUs contain a vibrating mass gyroscope which is small and inexpensive. A vibrating element is subjected to the Coriolis effect when it is rotated which causes a secondary vibration in the orthogonal direction. This vibration can be measured as a force and integrated in a formula to calculate the angular velocity. This angular velocity and the time between two measurements can be used to derive the orientation of the IMU.
Just like accelerometers, gyroscopes are not perfect either. They encounter problems such as drift, where the gyroscope does not come back to a zero-rate value after rotation. However, after combining the measurements from the accelerometer and gyroscope the resulting calculated orientation can already be quite accurate but to get an even better result a 3D magnetometer is used as a third measurement unit.

Magnetometer

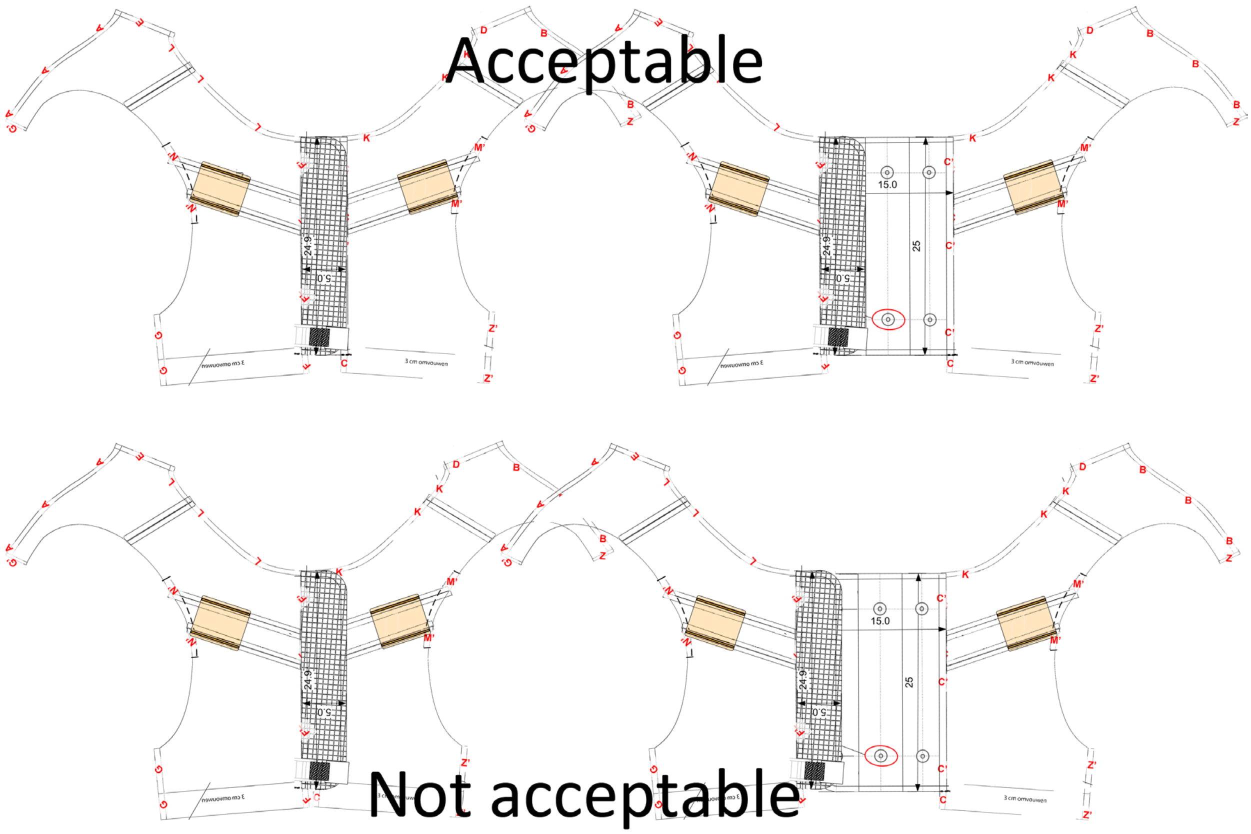
Magnetometers can correct any mistakes in the horizontal plane by referring to the measured magnetic field of the earth. Magnetometers work like a digital compass. They can only measure rotation on the horizontal plane or around the vertical axis, which makes up for the fact that the accelerometers cannot measure rotation around this axis. The only downside is that they do not work properly when there are other magnets or metal objects nearby.
All three of these sensors have their downsides but they all make up for each other resulting in pretty accurate measurements of orientation.

(Tan, 2012; Roetenberg, 2006)

B - Strap size

To determine whether the current vest is one-size-fits-all or not a test was done with 32 people. The test was performed with people from Xsens and it has determined what percentage of people can or cannot wear the vest. If it turns out that many people cannot wear it because it is either too small or too big than different sizes might be considered. This has to be discussed with Colleen.

During the test people had to put on the vest and the leftover Velcro was measured to determine if it was a good fit or not. The right side of the vest has a big Velcro strap of about 15 cm in width attached to it. The left side has a small piece of about 5 cm in width attached to it which can be stuck to the big strap. If a person is too big for the vest a part of the big piece will show, this is the part that was measured. Same goes for when a person is too small. The left piece will go over the right piece entirely and the surplus was measured. Acceptable measurements were between 0 and 10 cm. Anything below 0 means the vest is too big, anything above 10 means the vest is too small.



Apart from measuring the leftover Velcro, the chest width and shoulder width were also measured. If it turns out that multiple sizes are needed than that data can determine the sizes.

m(ale)/f(emale)	chest width (cm)	shoulder width (cm)	Velcro leftover (cm)
f	84	38	-3
f	84	41	-2
f	88	40	0
f	89	41	4
f	91	38	1
m	91	48	7
f	92	45	5
f	93	40	4
m	93	41	7
m	93	46	7
m	94	42	6
m	95	47	3
m	95	47	3
m	99	46	4
m	100	49	10
m	101	47	10
m	101	49	8
m	102	41	9
m	102	44	6
f	103	42	6
m	104	48	13
m	104	49	12
m	104	49	12
m	105	52	9
m	106	44	8
m	106	47	7
m	109	46	11
m	111	46	12
m	111	47	10
m	111	48	7
m	113	48	11
m	116	55	17
Average:	99,6875	45,34375	7
Sdev:	8,416640883	3,957661675	4,373213921
Dined data			
Average	101,1	44,5	
Sdev	14,6	3,4	

The data shows that about 70% of the people fit the current vest. However, when taking into account all of Xsens' costumers than this percentage will be smaller because every nationality and user is different. Asians are small for which the vest will be too big. Athletes are usually bigger which means the vest will be too small for them.
Three sizes are proposed based on data found using Dined. At first the sizes were proposed based on

the data found during the experiment, but after comparing it with Dined it turned out that the data was almost the same. Dined was still used because this data is probably more accurate than the data from the experiment.

The following sizes were proposed:

	Small	Medium	Large
Chest size:	80 cm - 95 cm	95 cm - 110 cm	110 cm - 125 cm
Shoulder width:	40 cm - 43 cm	43 cm - 46 cm	46 - 49 cm

It is up to Xsens to decide what to do with this proposal.

C - Stakeholders

Applications
- VR, training and simulation
- Ergonomics, use analysis
- Large test groups
- Biomechanics
- Revalidation

Stakeholder	Who/role	Values	Share	To take into account
General				
Any healthy adults	Performing with the straps	Proper movements are registered and can be analyzed	Contributing to movement science	Comfortable, easy to put on/take off, freedom of movement
Physically challenged people	Performing with the straps	Movements are registered and can be analyzed and perhaps used for rehabilitation	Contributing to movement science or for personal improvement	Comfortable, easy to put on/take off, freedom of movement
Technicians	Preparing use and use of results	Easy setup, results can immediately be used	Target group	Easy preparation and use of results
Maintenance	In case of an error need to fix this, in soft- or hardware	Earn money	Important for customer service	Parts to be replaced, software reachable for maintenance
Financing and funding	Financing straps	Improvement for company	Important subsidizers	Affordable, saving costs in other areas
VR, training and simulation				
Athletes	Optimization performance	Can optimize techniques	Important target group	Good placement of tracker, freedom of movement, fast movements possible
Trainers	Optimization training athletes	Analyze and optimize movements of athletes	Important target group	Freedom of movement, accurate results
Specialists	Analyze movement and suggest optimizations	Analyze and optimize movements	Important target group	Freedom of movement, accurate results
Ergonomics, use analysis				

Orthopedics, physiotherapists	Mocap may improve quality of work	Improve ergonomics of products	Important target group	Comfortable, freedom of movement, accurate results
ARBO	Better use analysis possible	Can strengthen their goals	Indirectly part of target group	Comfortable, freedom of movement
Insurance companies	Financial use	More efficiency in motion analysis	Approval	Efficient, accurate, freedom of movement
Large test groups				
Researchers	Analyzing motion of many test subjects for specific research	Quickly take off straps and put on next subject for large amount of results	Important target group	Efficient, easy to put on/take off, freedom of movement, accurate
Test subjects	Performing with straps	Movements can be analyzed	Important target group	Comfortable, easy to put on/take off, freedom of movement
Biomechanics				
Researchers	Analyzing all kinds of motion (i.e. gait analysis)	Broadening knowledge about human motion	Important target group	Accurate, freedom of movement, easy to put on/take off
Subsidizing committee	Financial use	More research with accurate results	Important subsidizer	Accurate, not too costly
Revalidation				
Orthopedics, physiotherapists	Improve quality of work	Improve revalidation possibilities	Important target group	Accurate, freedom of movement, easy to put on/take off
Revalidation patients	Personal physical improvement	Improve revalidation possibilities	Important target group	Freedom of movement, easy to put on/take off, comfortable
Insurance companies	Financial use	Better and more efficient way of working	Approval	Efficient, accurate, freedom of movement

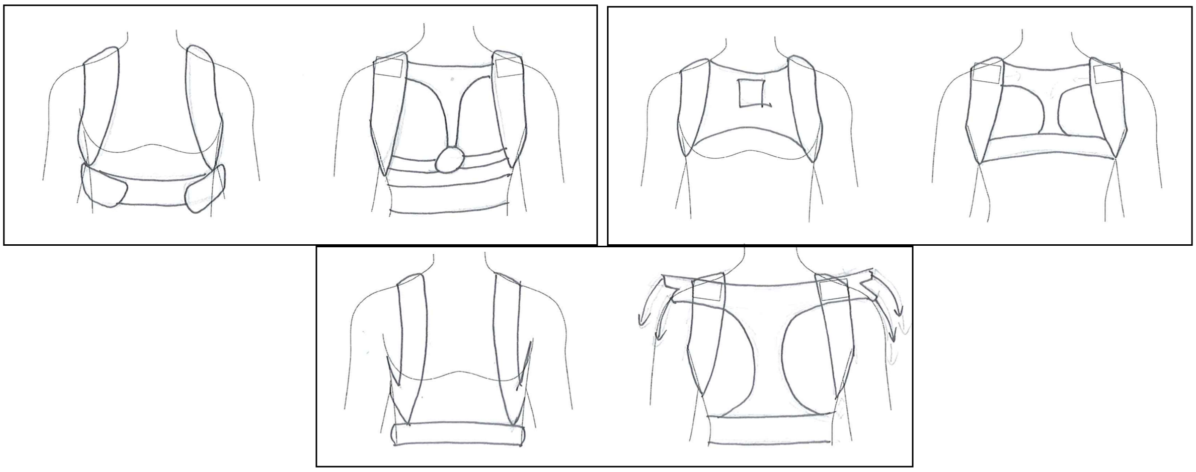
D - List of requirements

Requirements Design	**Quantification**
Accuracy	
Accuracy needs to be improved	Better accuracy than current strap
Limited movement skin with respect to the bone	
Limited movement strap with respect to the clothing or skin	
Limited movement sensor with respect to the strap	
The strap must not affect movement of the user	
It must be spatially accurate in terms of the positions of the user's joints	At the predefined positions +/- 1 mm
The placement of the sensors must be as assumed in the software	On top of the spine of the scapula
The placement of the sensor with respect to the joints must be clear to the user	
It should capture detailed motion as well as gross body motion	
It should capture fast motion as well as slow body motion	
It should adjust to the shape of the shoulder	
It should not force the shoulders in a certain position	
The piece has to be combined with the sternum tracker	
User friendliness	
Few sizes	Preferably 3 - 5
Putting on/ taking off should be fast, easy and accurate	For entire straps not longer than 10 min
No fixations	
No sharp edges	
No friction	
No irritation of the skin because of friction	
It should be comfortable	
It should not restrict movement	
It should not be too tight	
Can be worn over clothing	
Can be worn on bare skin	
Wearable by physically challenged people	
Easy and quick placement of sensors	For entire straps not longer than 15 min
Quickly exchangeable between people	
Can be put on with the help of max. 1 person	
Aesthetics	
Preferably maintain coherence and presentation current straps	
It should invite the user to wear it	

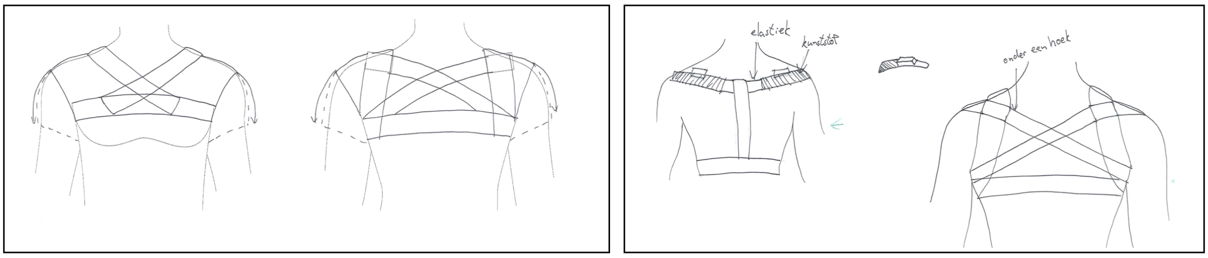
Not too many loose bands	
Material	
Durable/maintain elasticity	
Colorfast	
No allergic reactions	
Wearable in extreme conditions	-20 - +55°C, non-wet
No use of metals	
Lightweight	
Desires	
It can be put on without help	
Measurements should mimic results from the experiment	Same results as when placing trackers directly on skin
Wearable by children	Needs smaller size

E - Concept generation

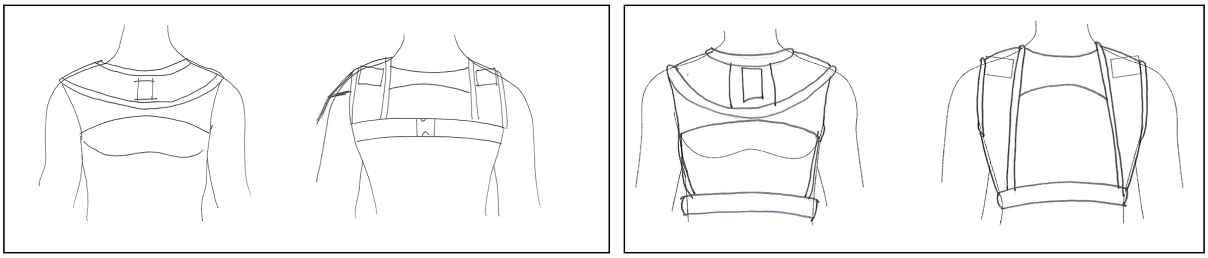
The ideas that were generated can be divided into five groups:
Ideas that use lycra or elastic straps at the back that pull the sensor both inwards and downwards.



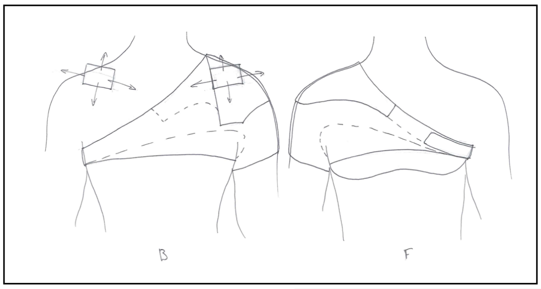
Ideas that use textile straps to pull the sensors in place.

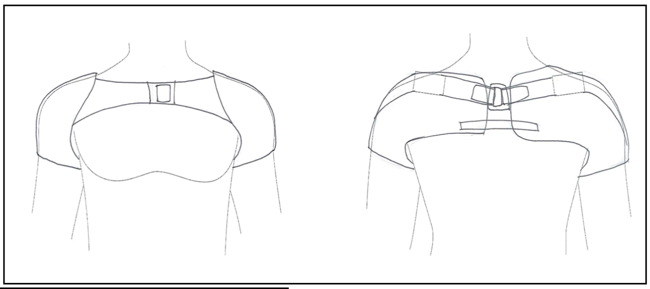


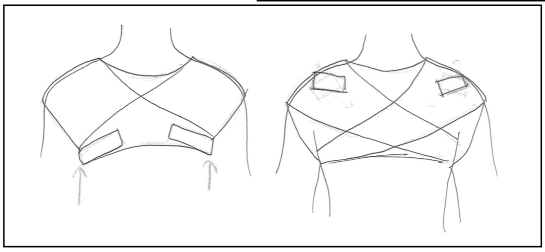
Ideas that use lycra straps with elastic bands as reinforcements on the sides.



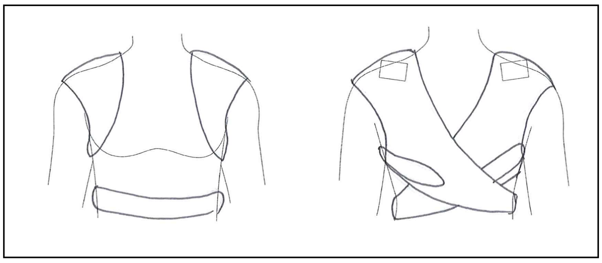
Ideas that use tight fitting neoprene.

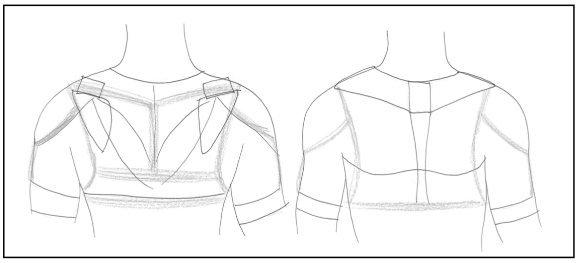


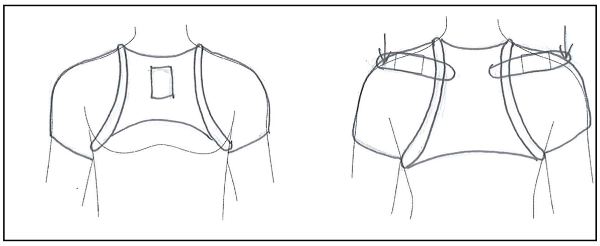


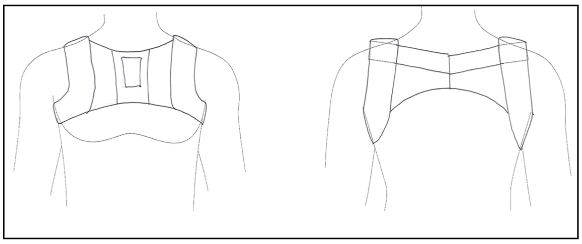


Ideas that do not fit in any of these categories.









F - Experiments

Protocol for the first experiment

1 - The purpose of the experiment will be explained to the participant.
- To test the prototypes on functionality and freedom of movement.

2 - The different movements that the participant has to perform will be explained and shown:
- Basic N-pose;
- Abduction with both arms, five times, until hands touch;
- Flexion with both arms, five times, to 90°;
- Shrugs with both shoulders, five times;
- Hands touch and move arms in front of body for 15 seconds.

3 - Photographs will be taken from the front, the side and the back when the participant performs:
- N-pose;
- Abduction with both arms when hands touch;
- Flexion with both arms to 90°;
- Shrugs with both shoulders;
- Hands touch in front of body.

4 - The MVN straps (full body) will be put on except for the shoulder piece.
5 - The shoulder and sternum sensors will be put on the skin using double sided tape.
6 - The system will be calibrated (N-pose, hand touch, nose point).
7 - Photographs will be taken from the front, the side and the back when performing the N-pose.
8 - The participant is asked to move around freely for a minute.
9 - Photographs will be taken from the front, the side and the back when performing the N-pose.
10 - The positions of all sensors are checked and the straps will be adjusted where necessary.
11 - The participant will be asked to perform all the movements five times while recording each movement separately in MVN Studio and with a camera:
- Abduction with both arms until hands touch;
- Flexion with both arms to 90°;
- Shrugs with both shoulders;
- Hands touch and move arms in front of body for 15 seconds.

12 - Photographs will be taken from the front, the side and the back when performing the N-pose.
13 - The participant is asked a few questions about the freedom of movement.
14 - The sensors will be taken off the skin and will be put in the current shoulder piece.

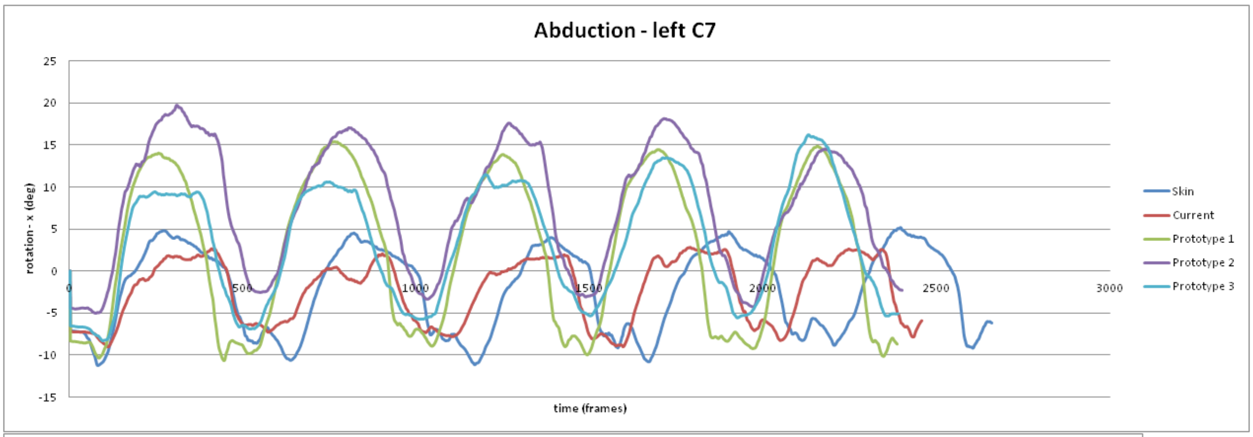
15 - The current shoulder piece will be put on.
16 - The system will be calibrated (N-pose, hand touch).
17 - Photographs will be taken from the front, the side and the back when performing the N-pose.
18 - The participant is asked to move around freely for a minute.
19 - Photographs will be taken from the front, the side and the back when performing the N-pose.
20 - The positions of all sensors are checked and repositioned where necessary.
21 - The same movements will be performed five times while recording each movement separately in MVN Studio and with a camera.
22 - Photographs will be taken from the front, the side and the back when performing the N-pose.
23 - The participant is asked a few questions about the user friendliness and freedom of movement of the prototype.
24 - The current shoulder piece will be taken off and the sensors will be put in the first prototype.

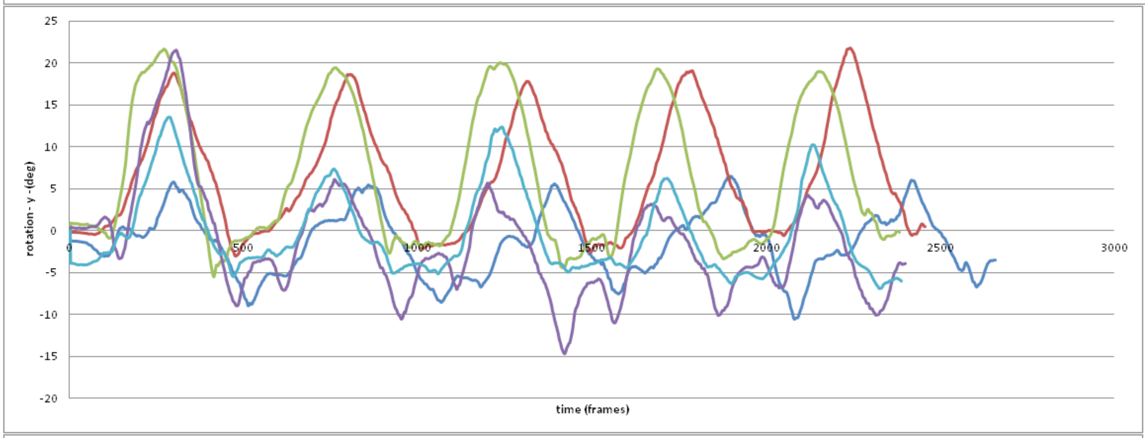
25 - The prototype will be put on.
26 - The system will be calibrated (N-pose, hand touch).
27 - Photographs will be taken from the front, the side and the back when performing the N-pose.
28 - The participant is asked to move around freely for a minute.
29 - Photographs will be taken from the front, the side and the back when performing the N-pose.
30 - The positions of all sensors are checked and repositioned where necessary.
31 - The same movements will be performed five times while recording each movement separately in MVN Studio and with a camera.
32 - Photographs will be taken from the front, the side and the back when performing the N-pose.
33 - The participant is asked a few questions about the user friendliness and freedom of movement of the prototype.
34 - The sensors will be put into the next prototype.
35 - Repeat steps 24 – 34 for all the prototypes.

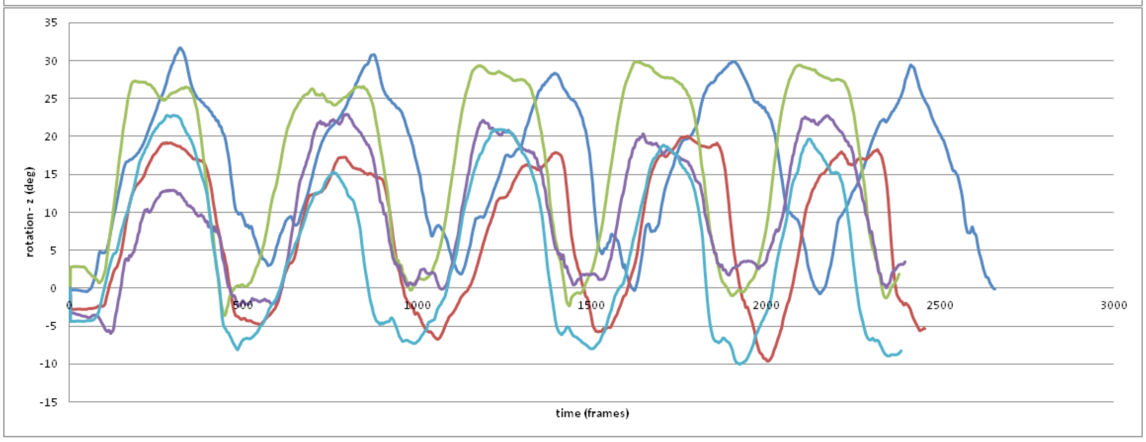
G - Results

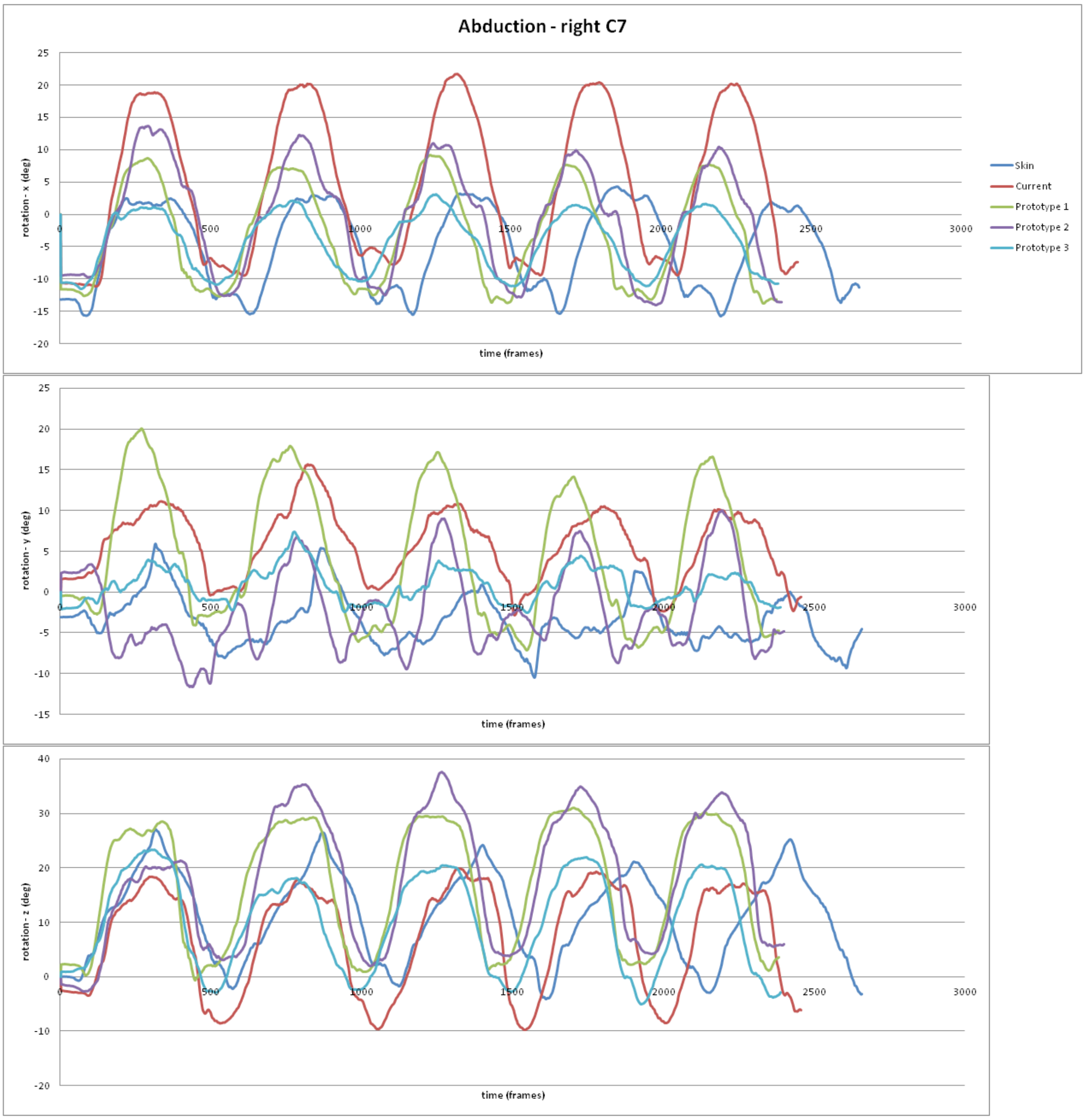
These are the resulting graphs from the experiments done with the prototypes. The graphs show the rotation in x, y and z of the left and right C7 segments and the left and right shoulder segments during abduction, flexion and shrugs. A fourth graph shows the results of the handtouch experiment, it shows the distance between both hands over time. In every graph the dark blue line represents the reference or the results from the skin-taped sensors. The red line shows the result from the current shoulder piece. The green line represents the first prototype. The purple line is the second prototype and the light blue line is the third prototype. The graphs are grouped by participant.

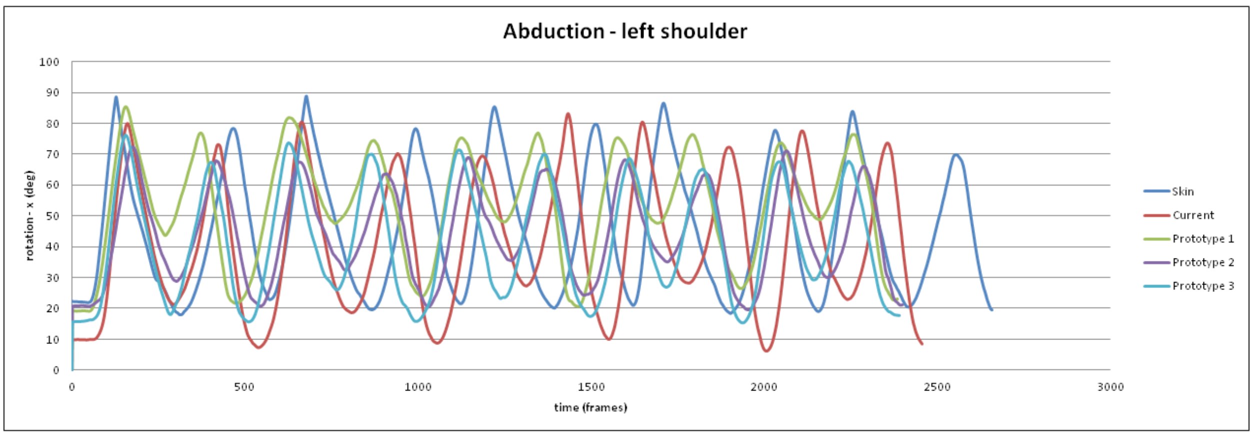
Participant 1

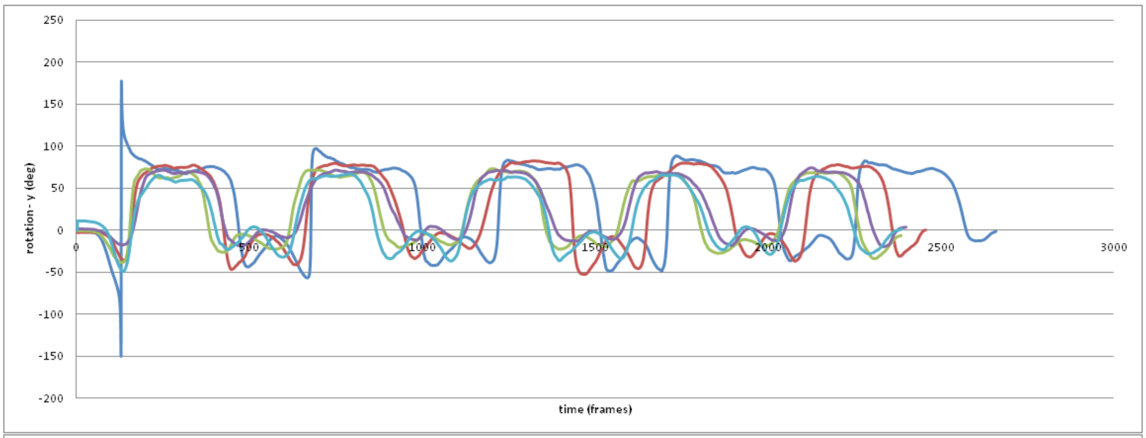


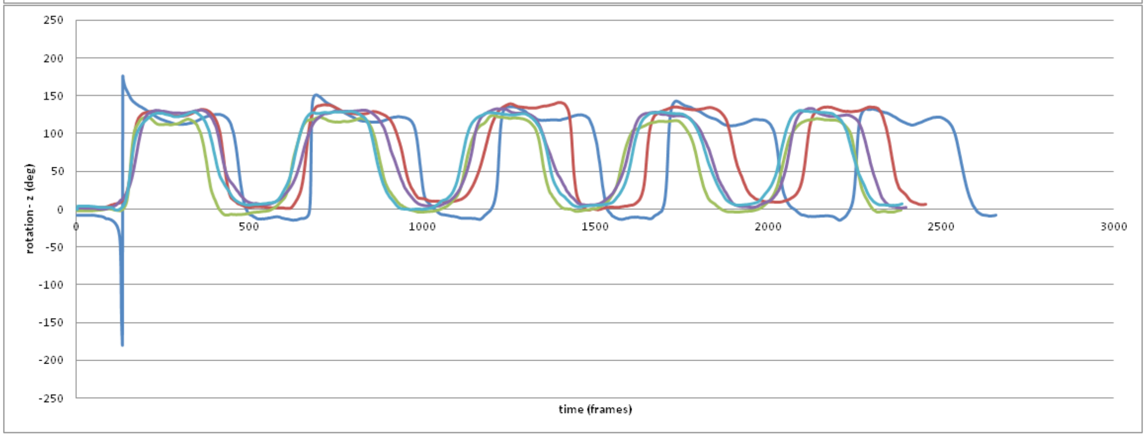


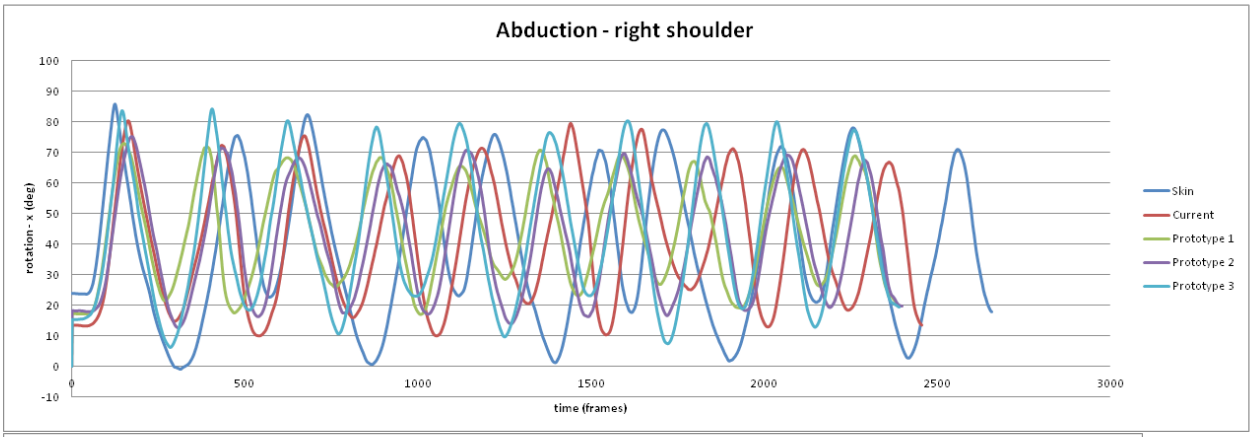


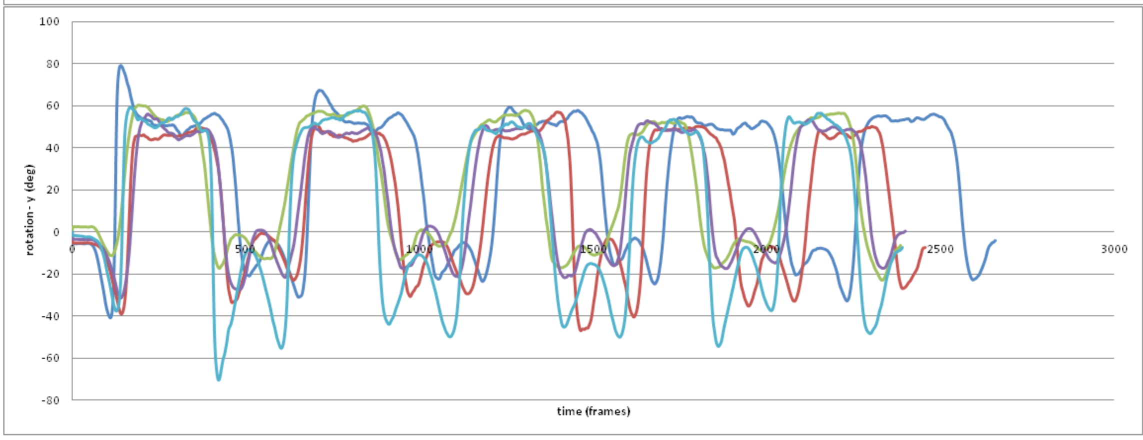

Abduction - right C7
rotation - x (deg)
rotation - y (deg)
rotation - z (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

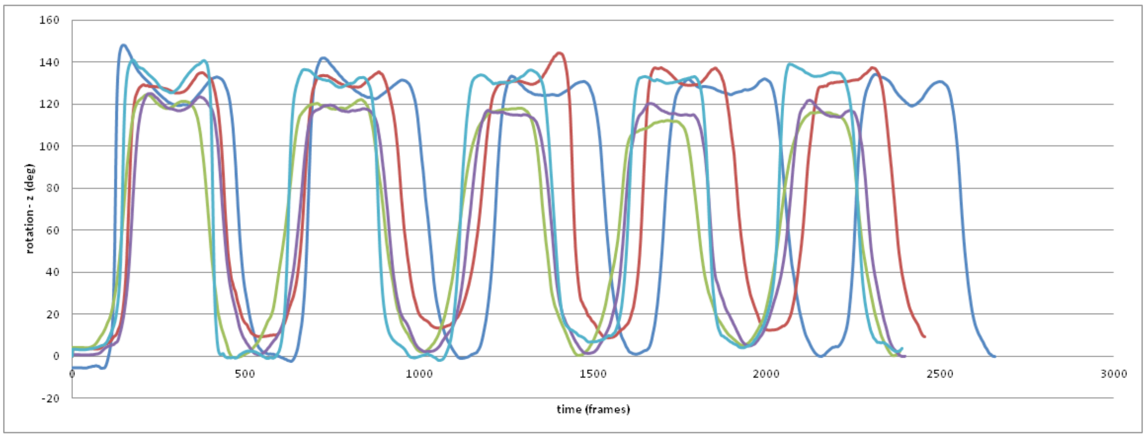

Abduction - left shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3


rotation - y (deg)
time (frames)

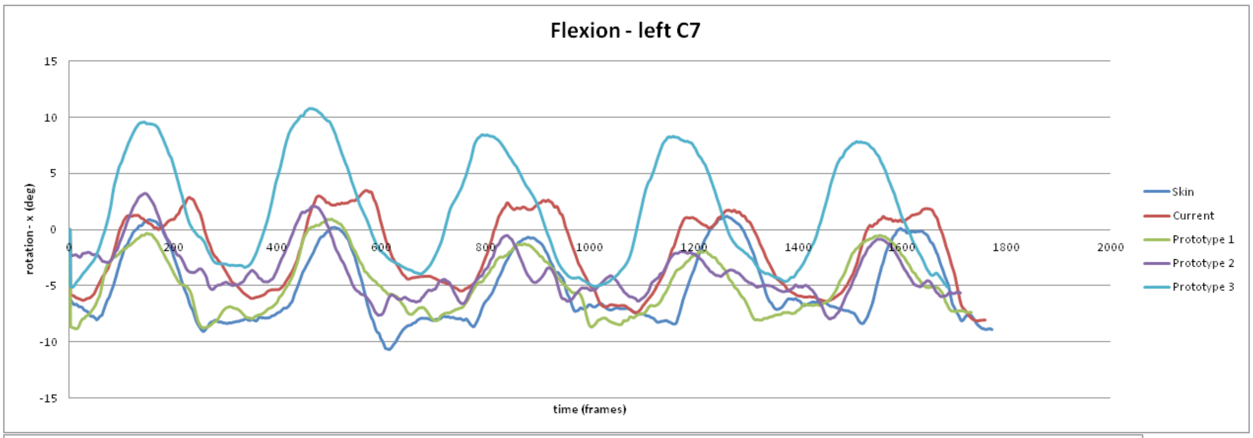

rotation - z (deg)
time (frames)


Abduction - right shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

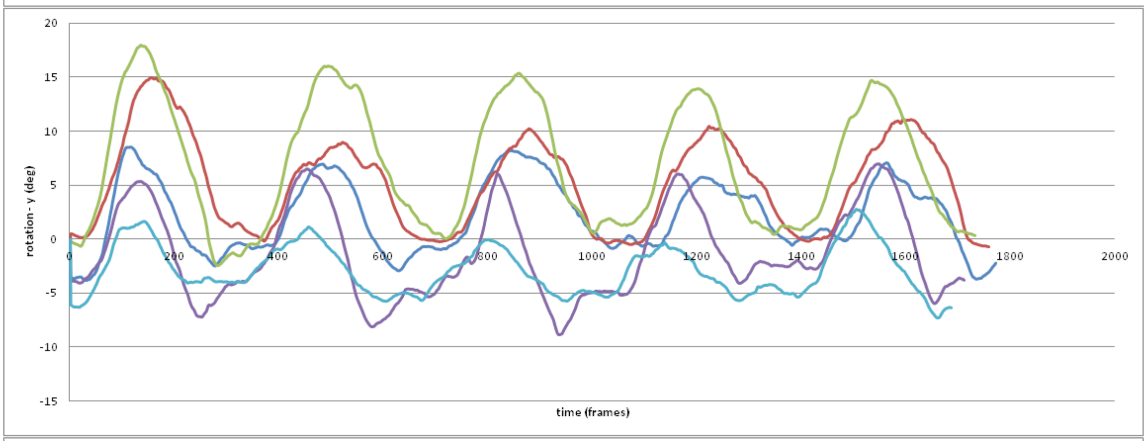

rotation - y (deg)
time (frames)



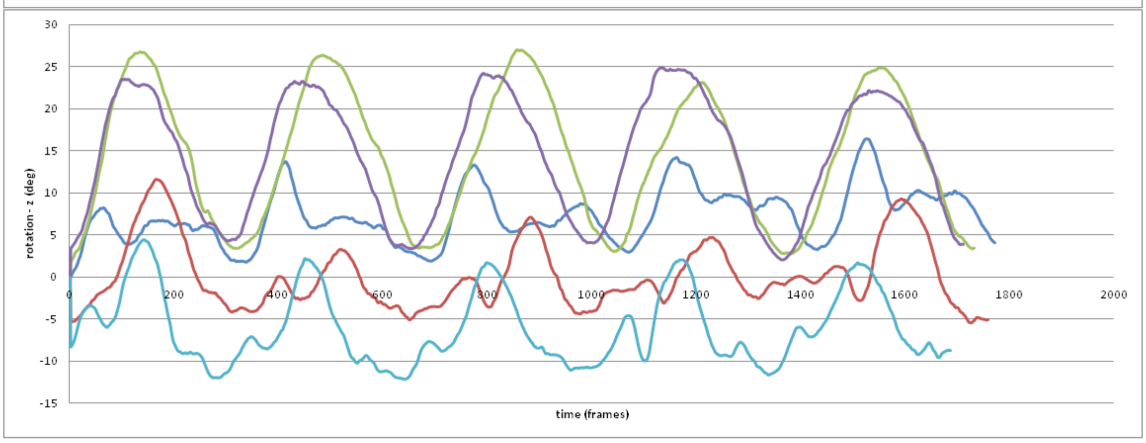
rotation - z (deg)
time (frames)



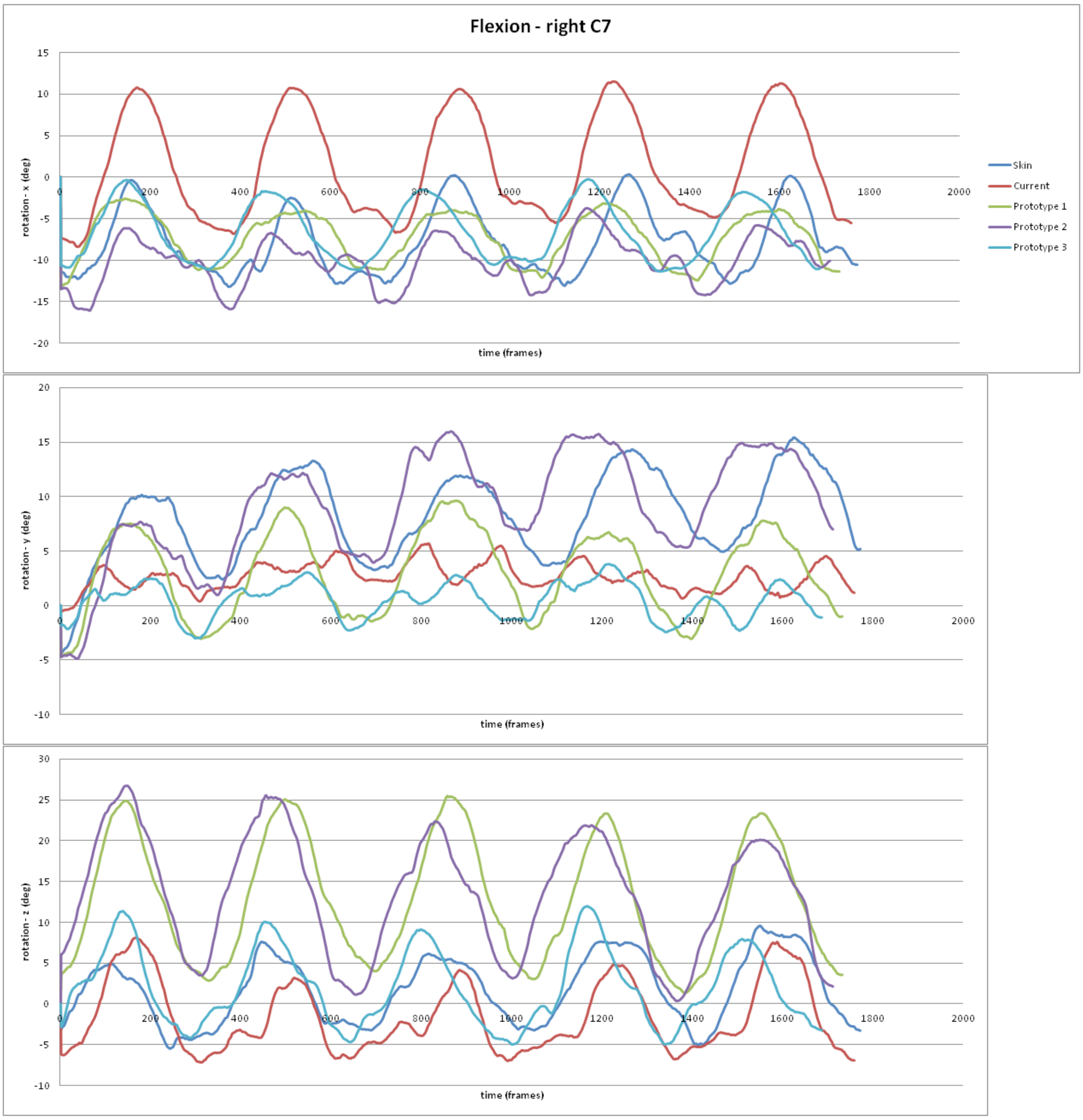
Flexion - left C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3



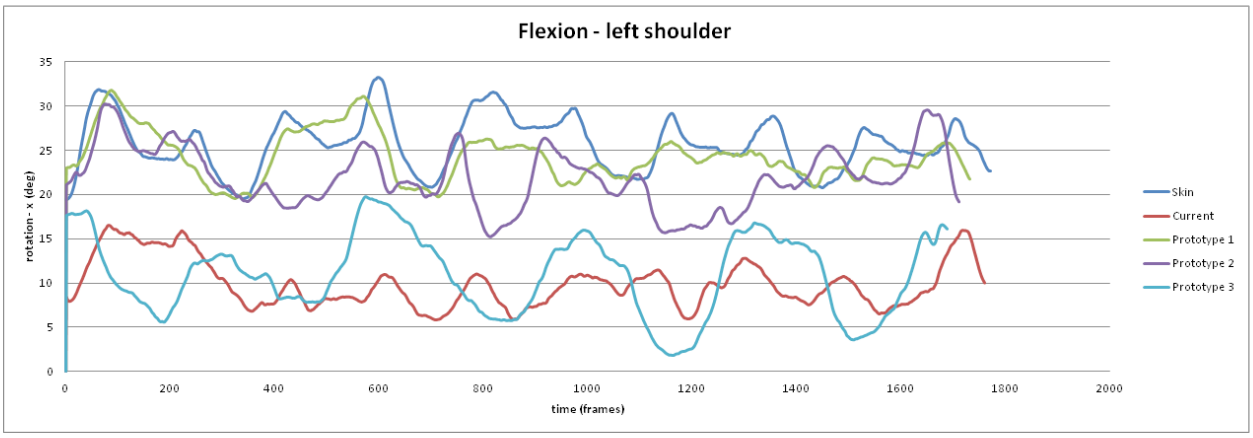
rotation - y (deg)
time (frames)



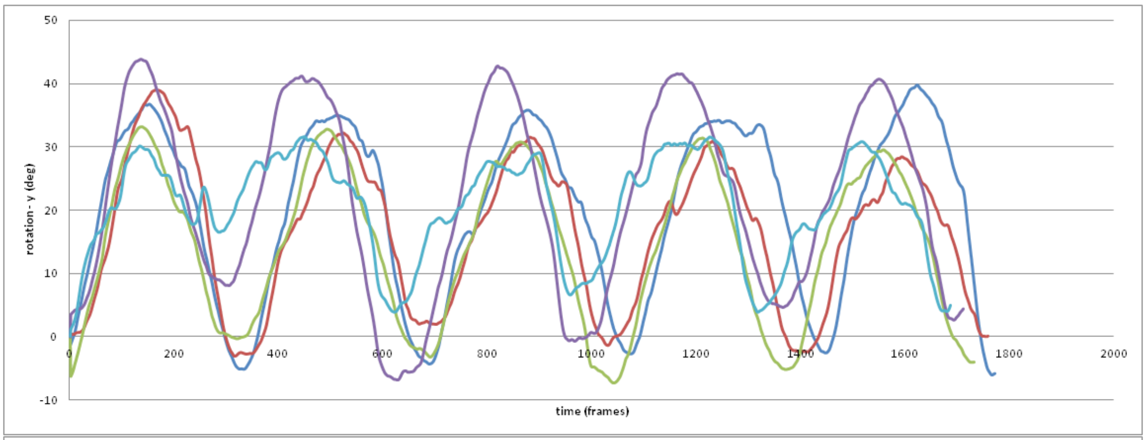
rotation - z (deg)
time (frames)

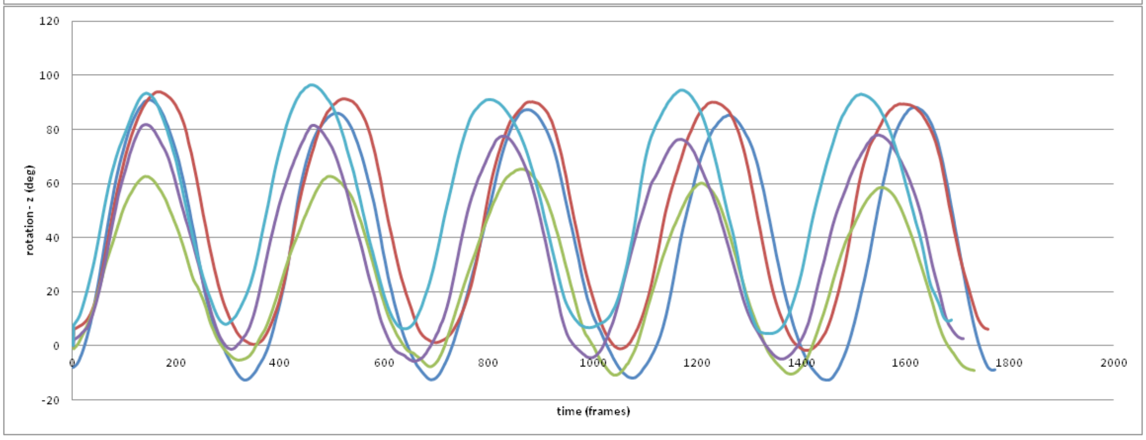


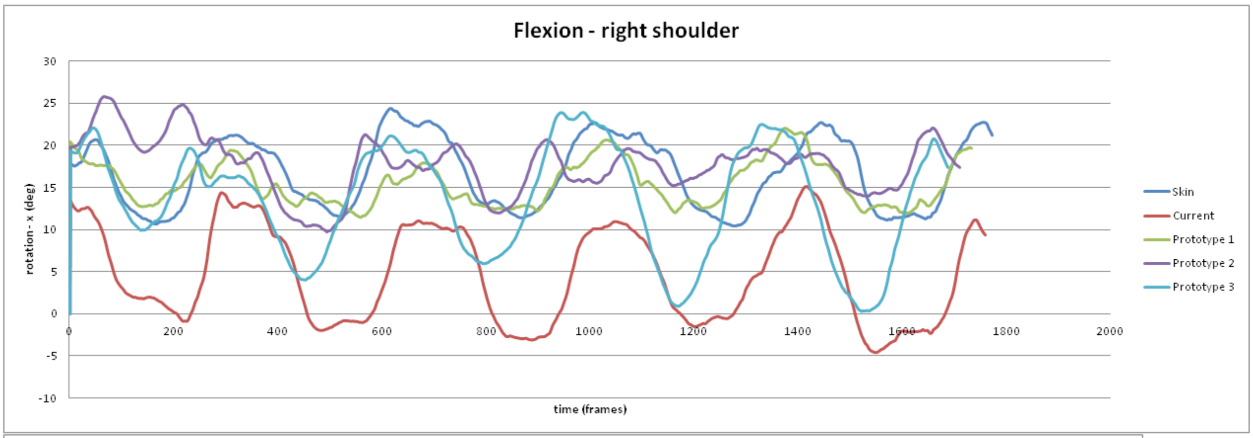
Flexion - right C7
rotation - x (deg)
rotation - y (deg)
rotation - z (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

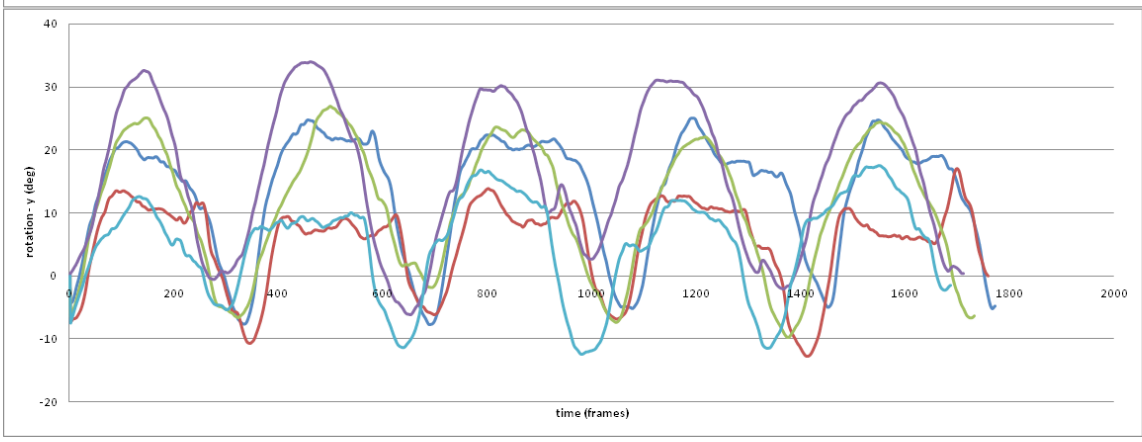


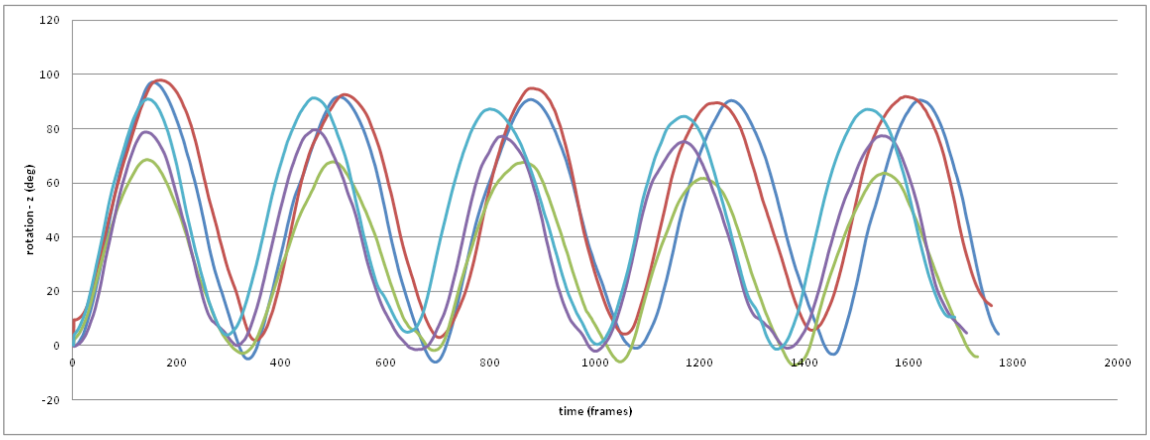
Flexion - left shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

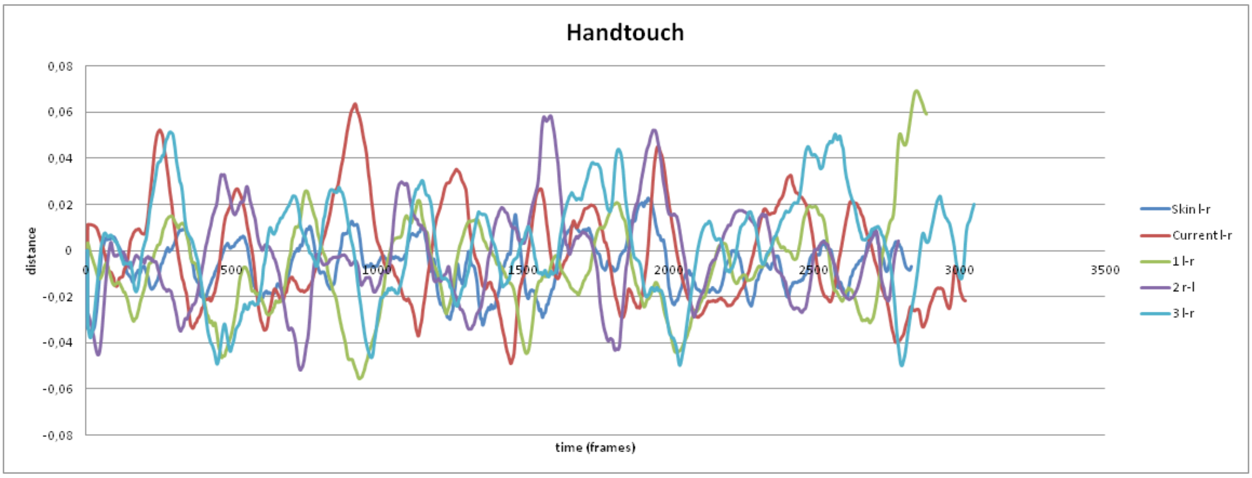

rotation - y (deg)
time (frames)

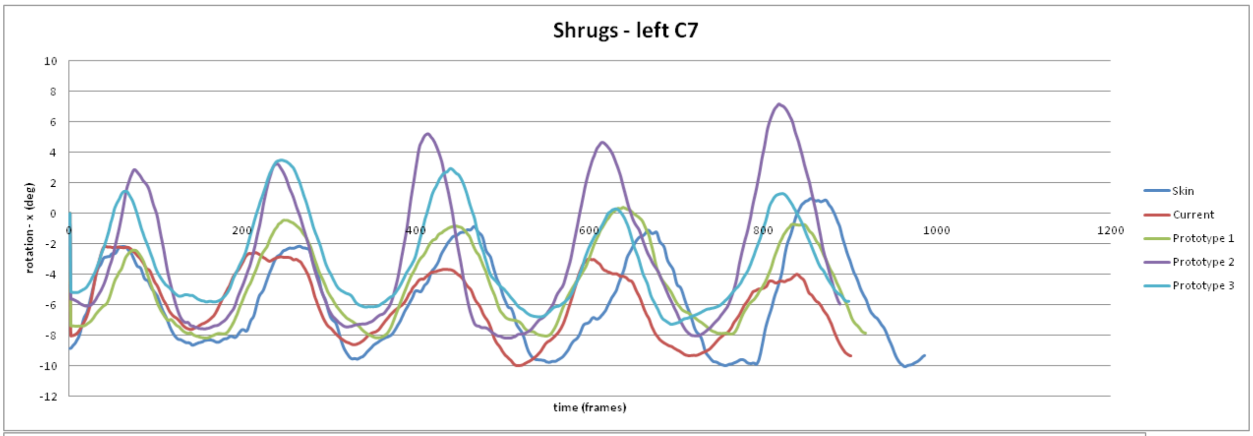

rotation - z (deg)
time (frames)

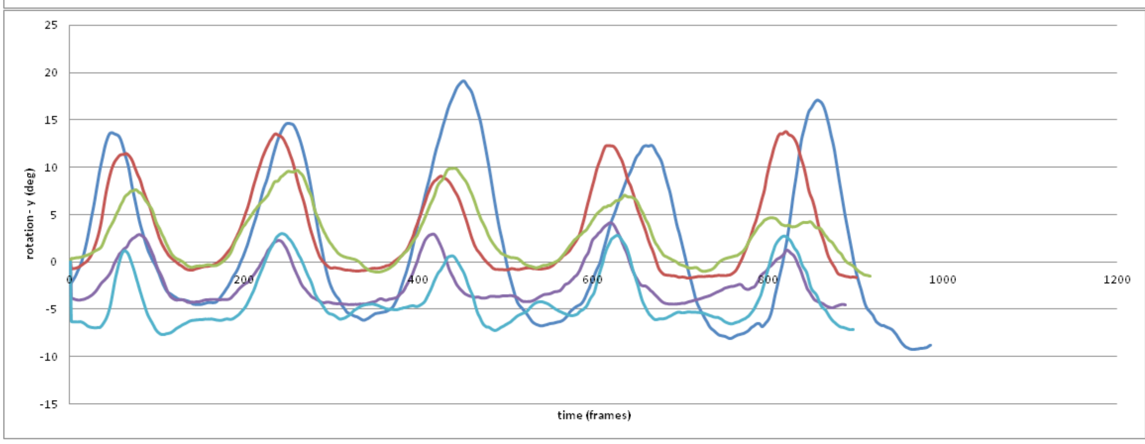

Flexion - right shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

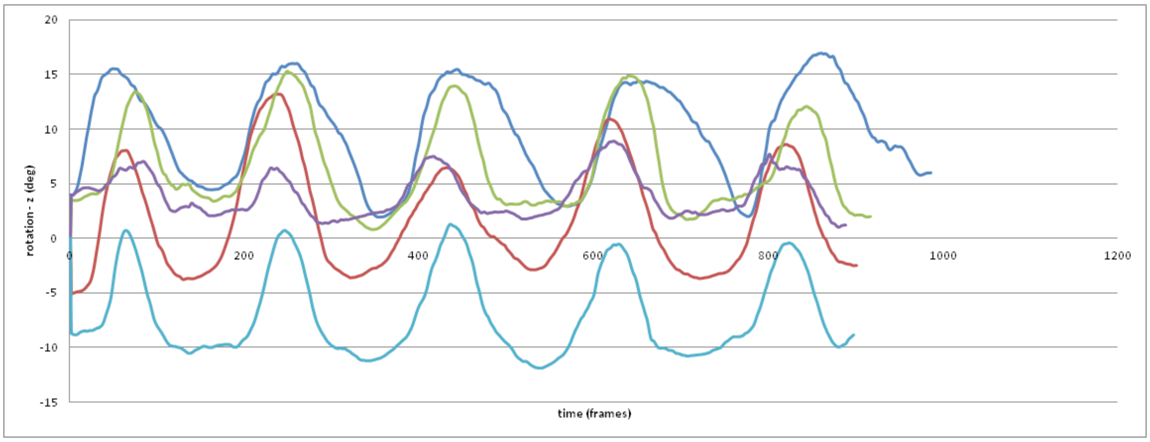

rotation - y (deg)
time (frames)

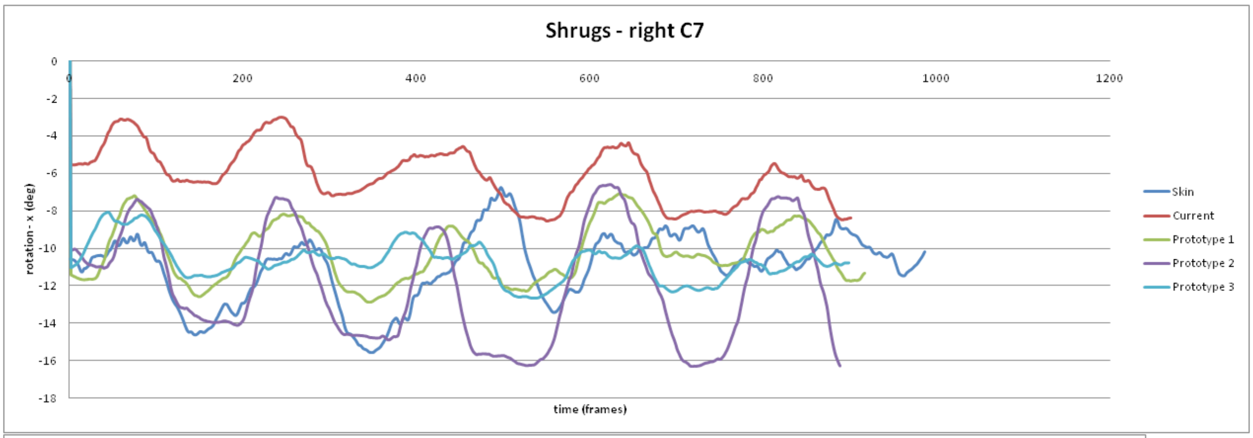

rotation - z (deg)
time (frames)

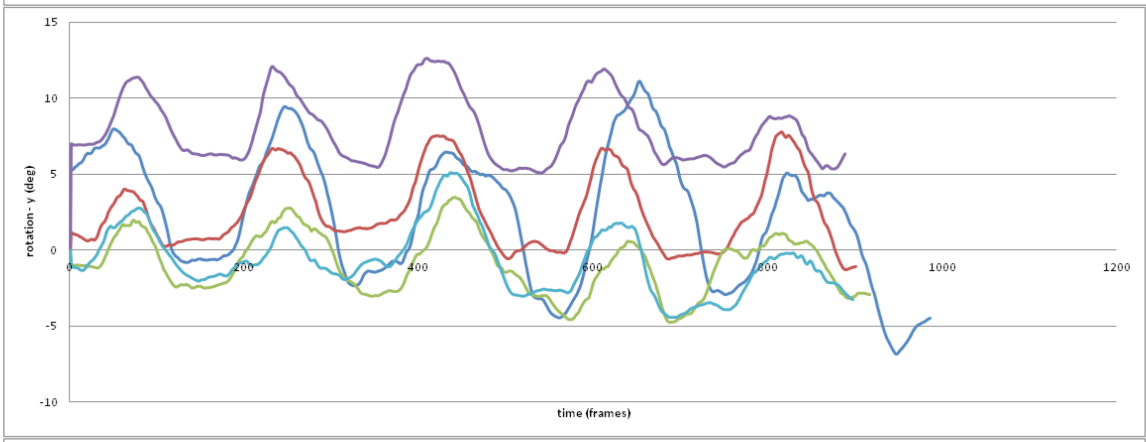

Handtouch
distance
time (frames)
Skin l-r
Current l-r
1 l-r
2 r-l
3 l-r

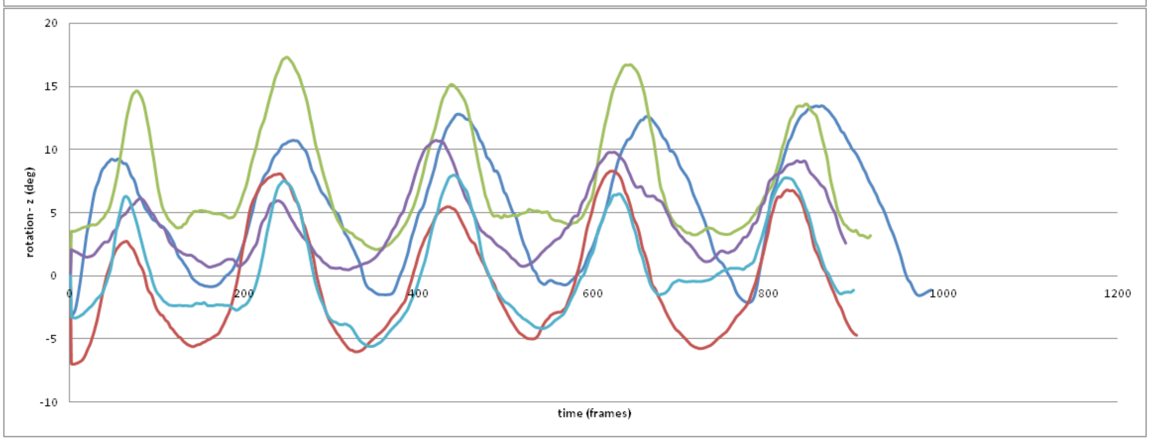

Shrugs - left C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3


rotation - y (deg)
time (frames)

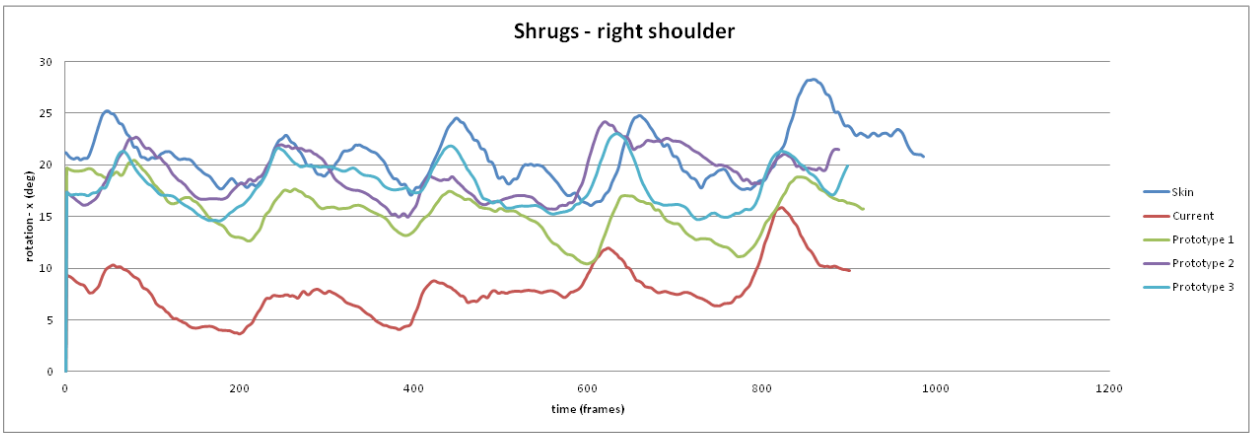

rotation - z (deg)
time (frames)

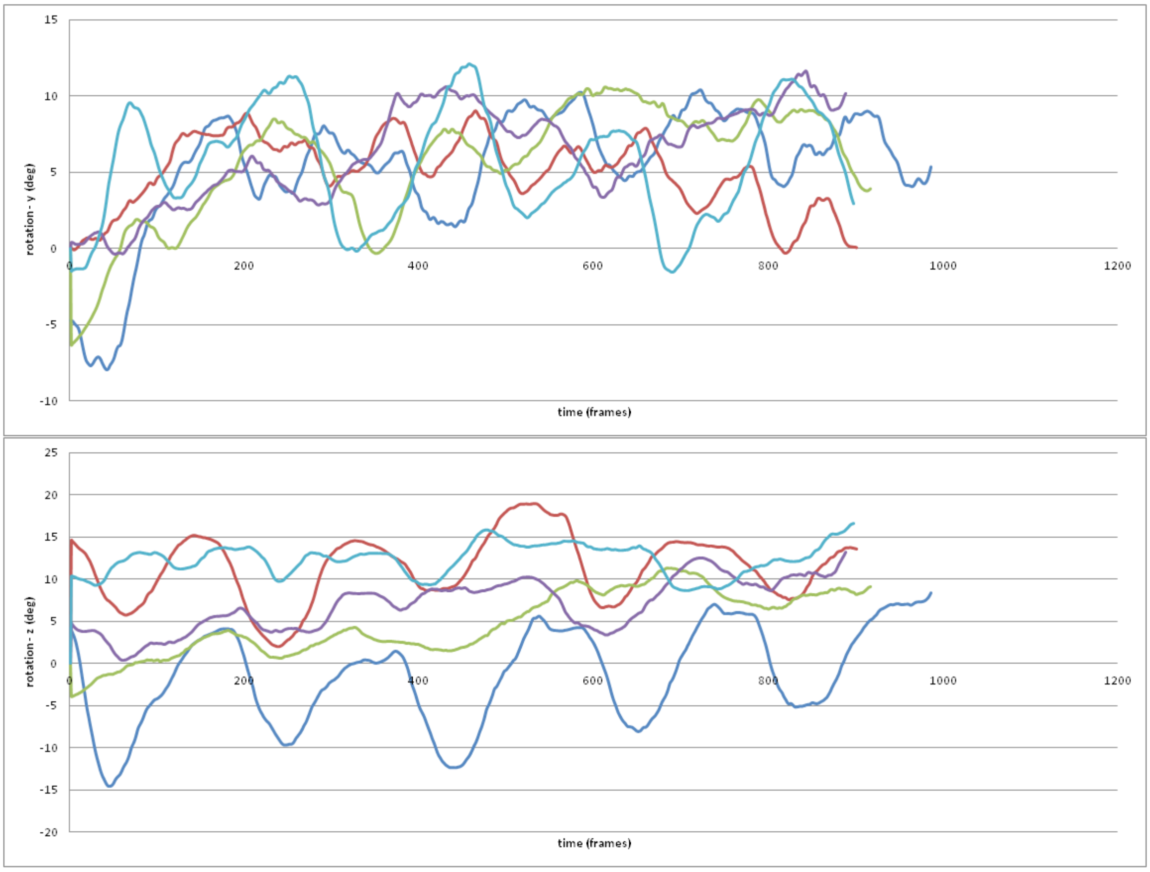

Shrugs - right C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

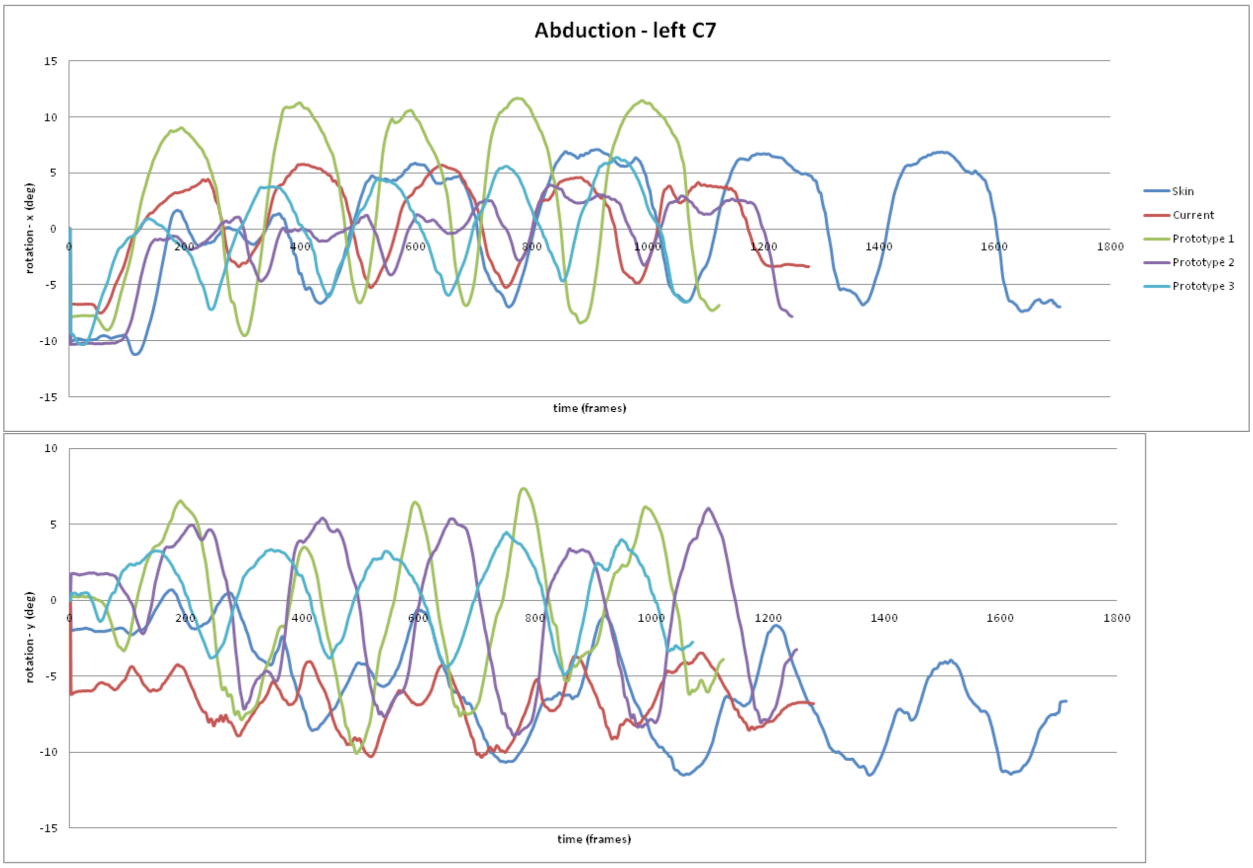

rotation - y (deg)
time (frames)

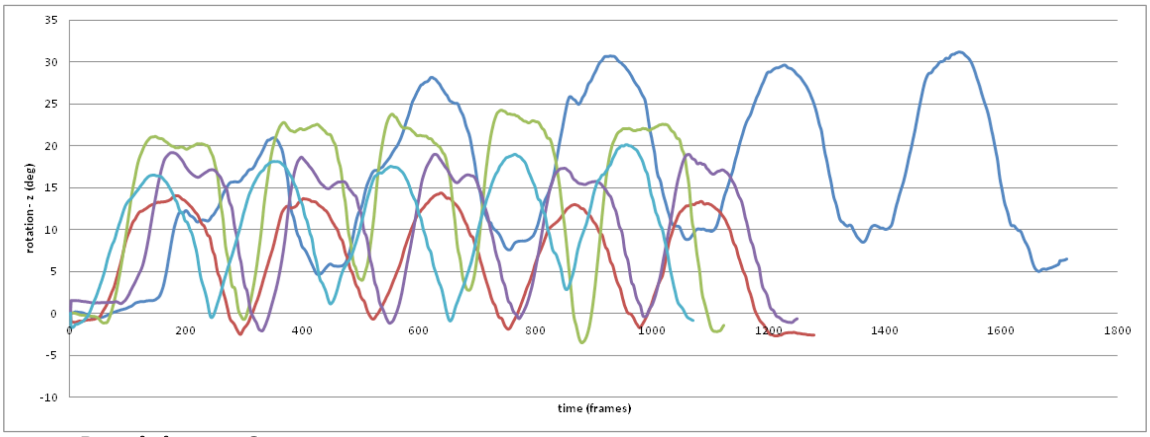

rotation - z (deg)
time (frames)


Shrugs - left shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3
rotation - y (deg)
time (frames)
rotation - z (deg)
time (frames)

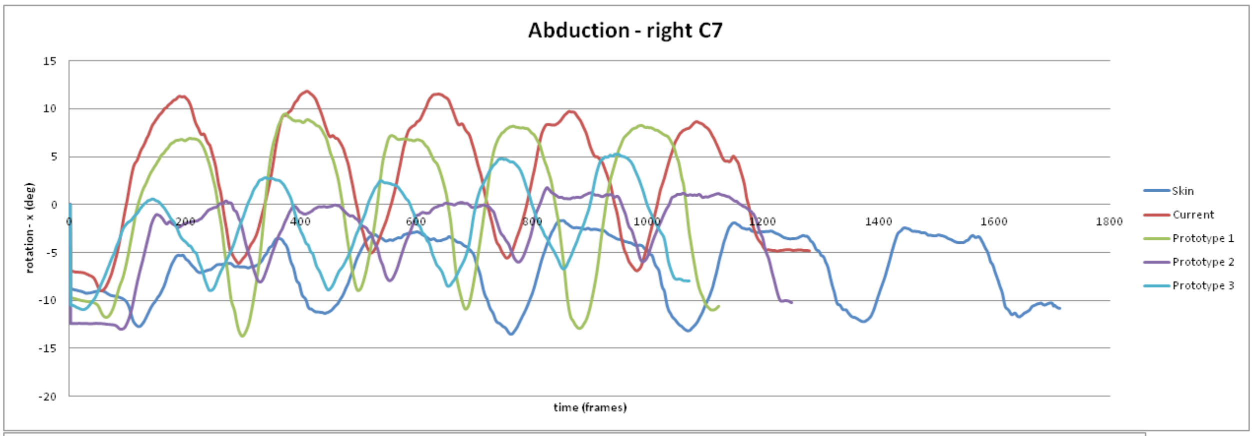

Shrugs - right shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

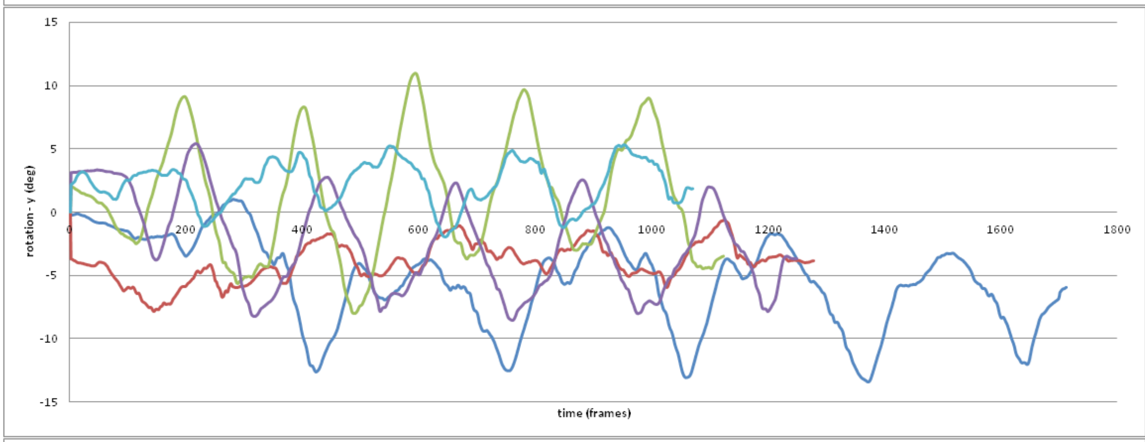

rotation - y (deg)
time (frames)
rotation - z (deg)
time (frames)

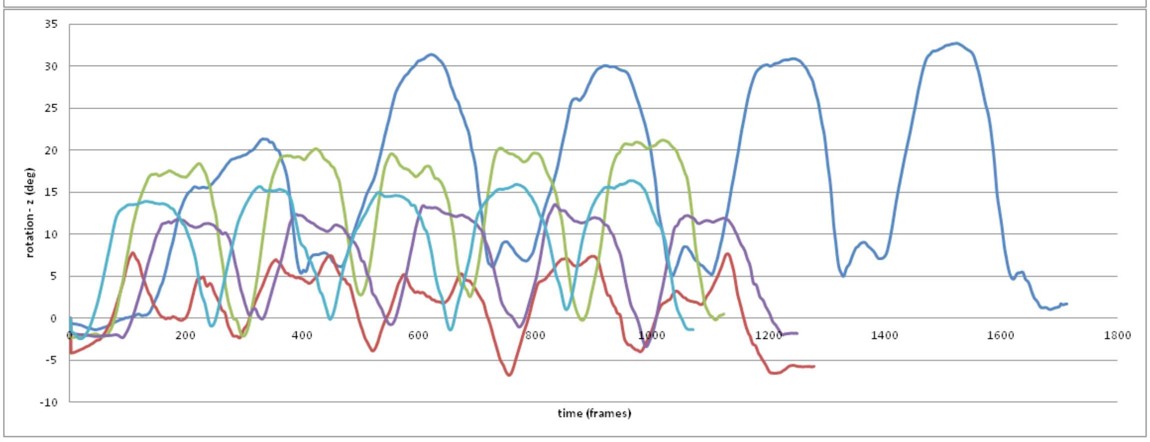

Abduction - left C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3
rotation - y (deg)
time (frames)

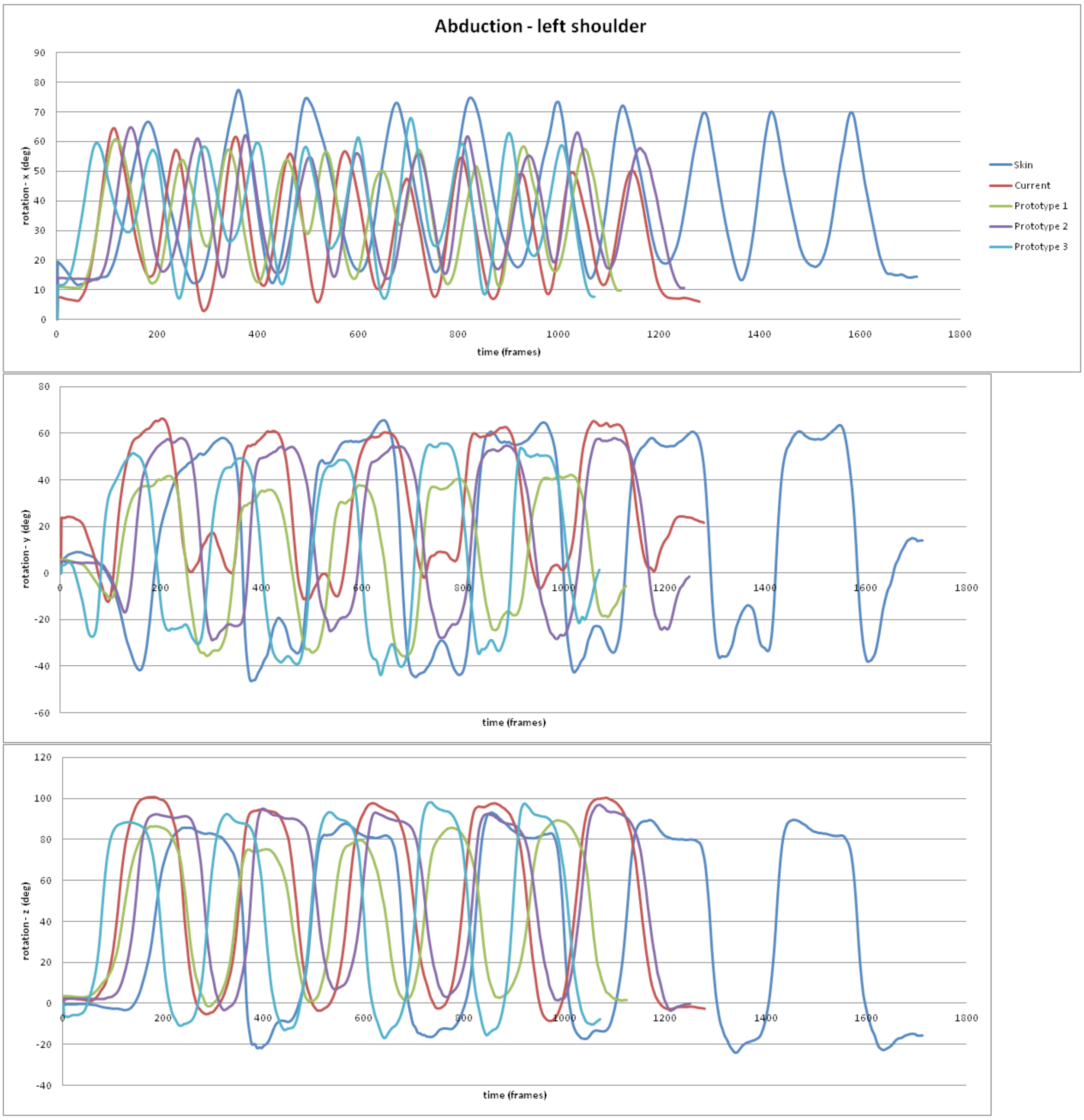


Participant 2

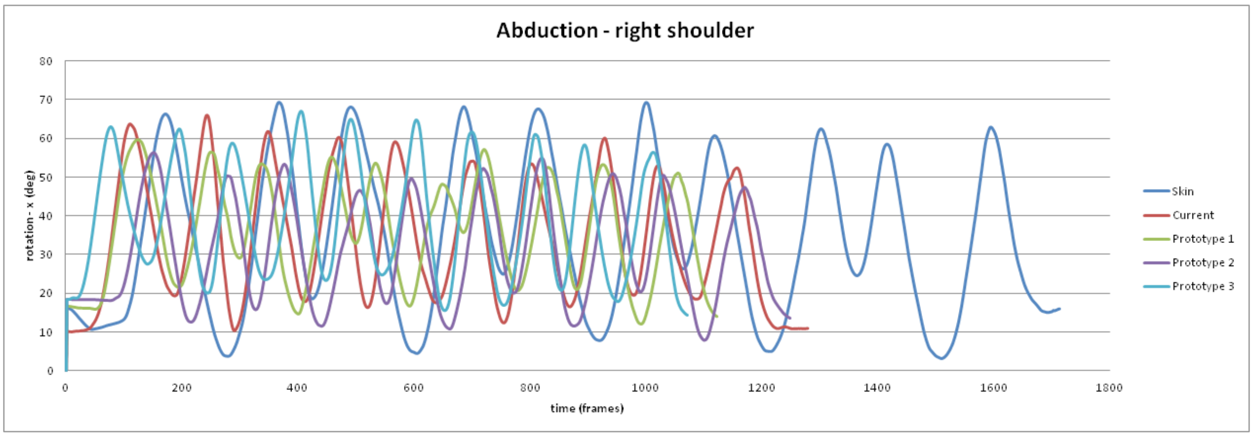




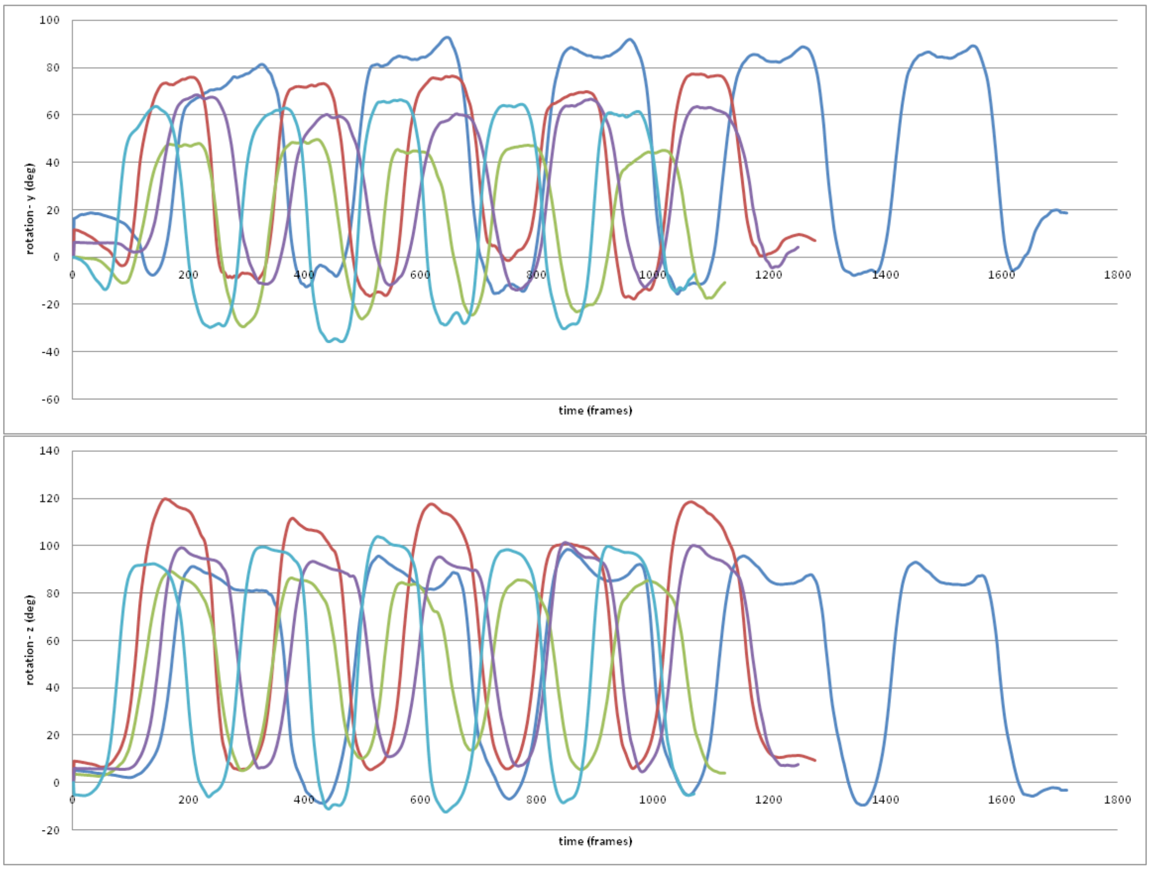


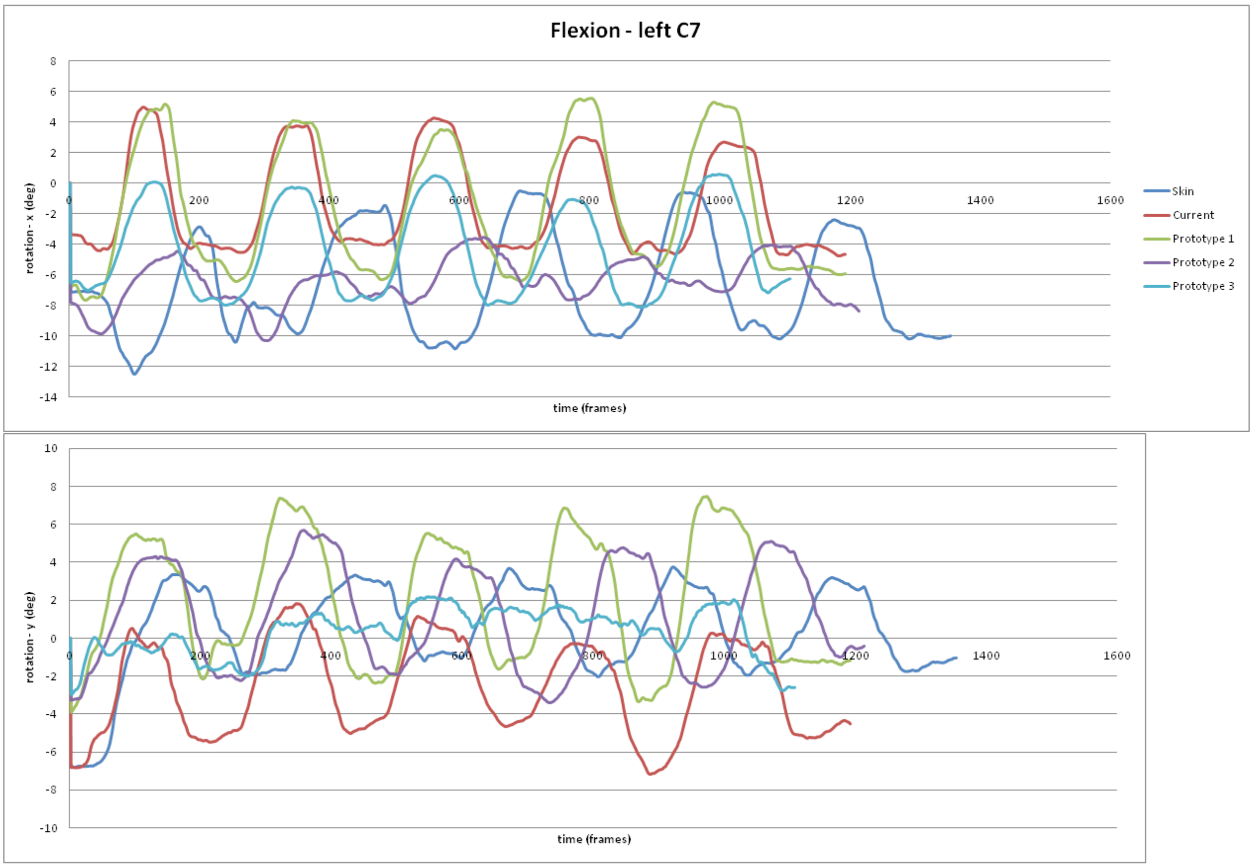


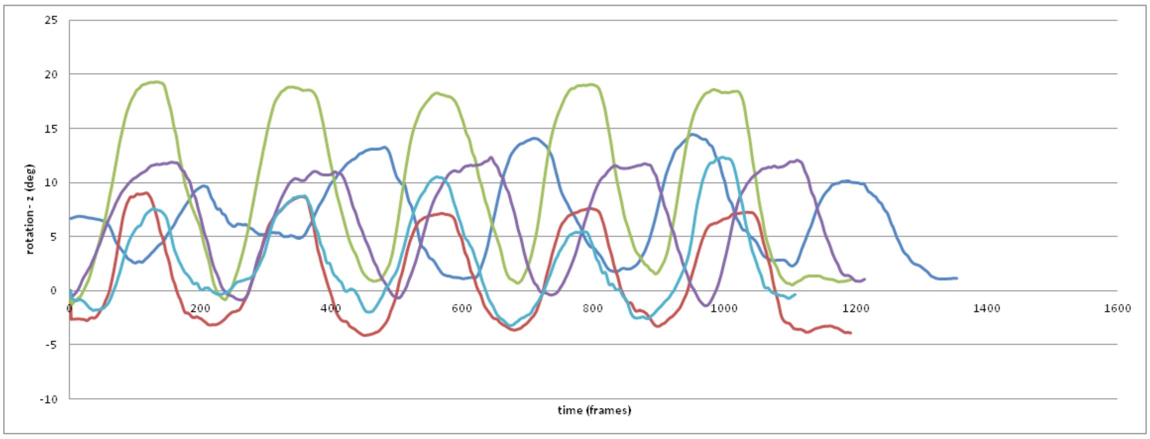
Abduction - left shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3
rotation - y (deg)
time (frames)
rotation - z (deg)
time (frames)

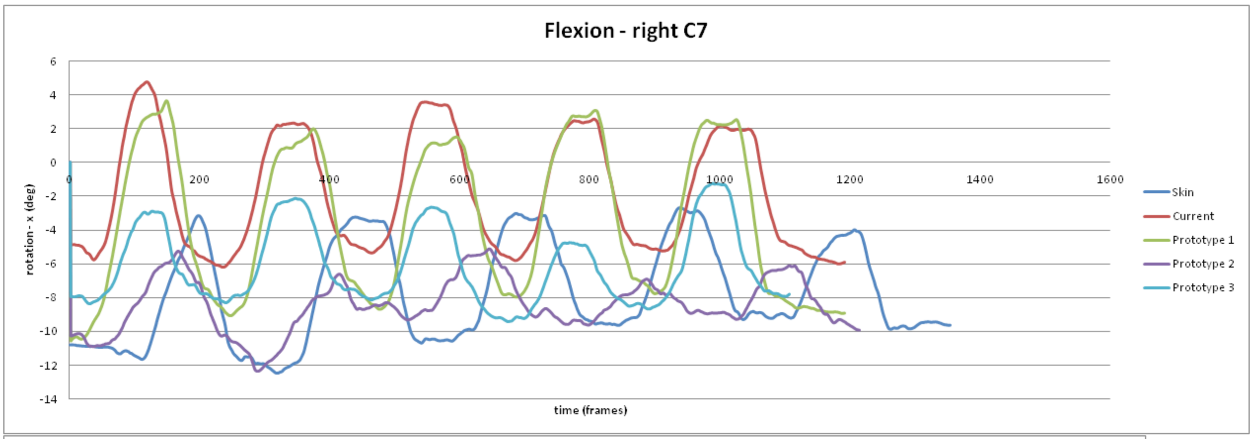


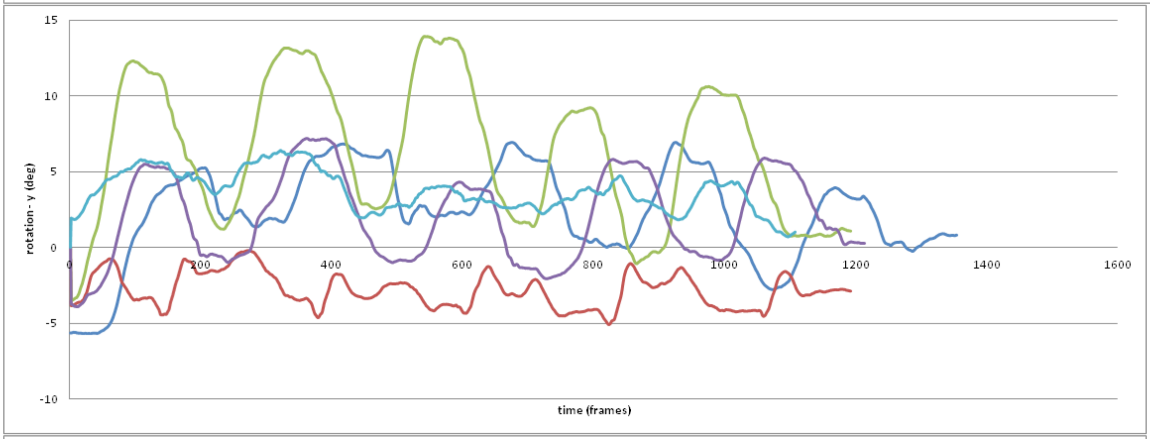
Abduction - right shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

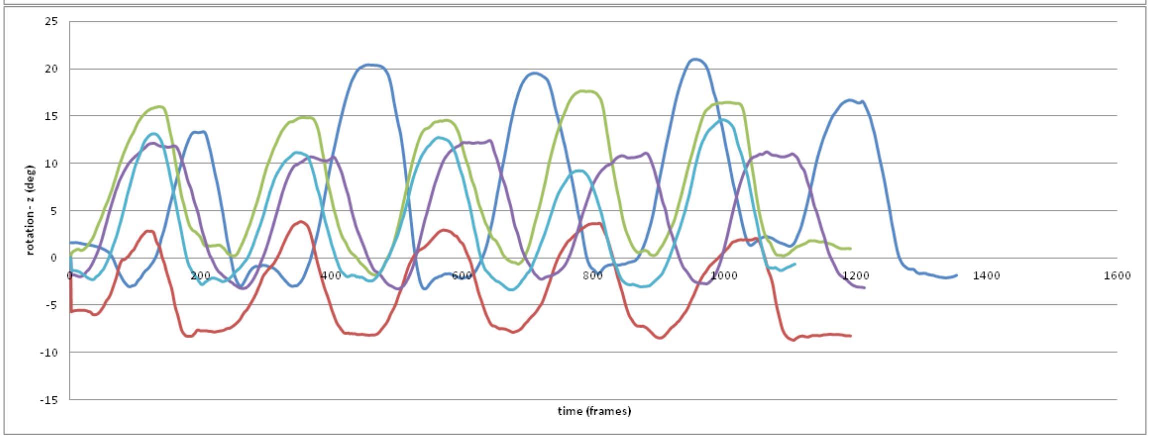

rotation - y (deg)
time (frames)
rotation - z (deg)
time (frames)

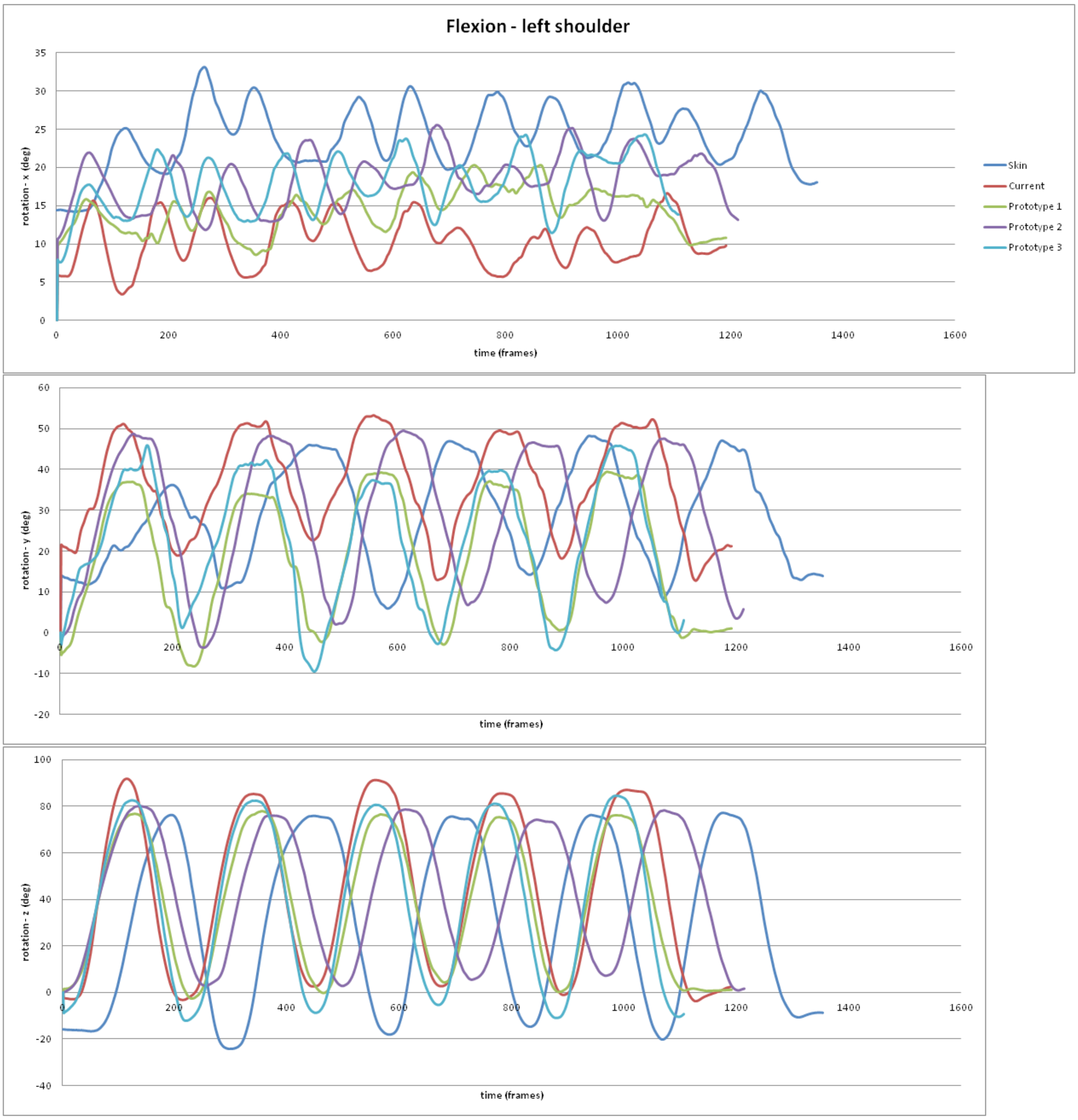

Flexion - left C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3
rotation - y (deg)
time (frames)

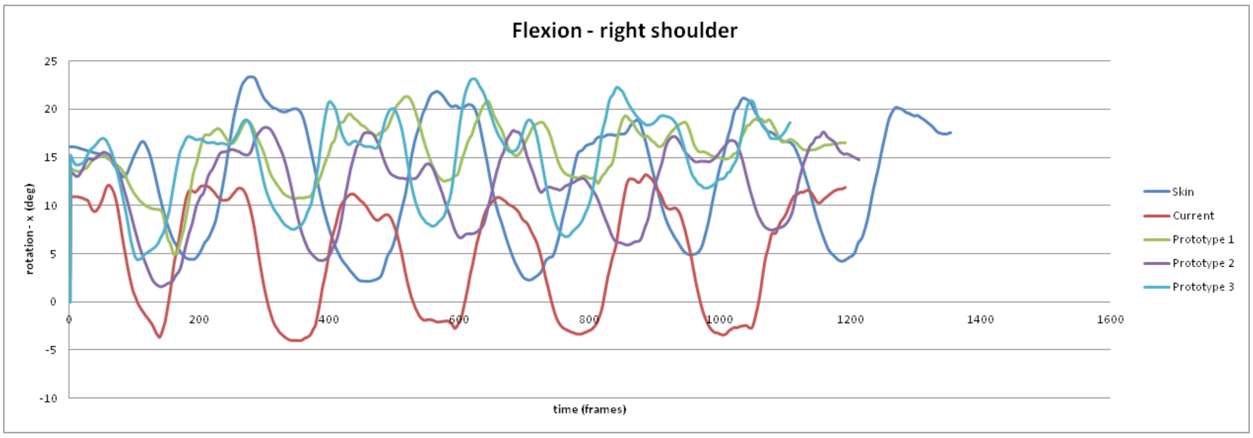

rotation - z (deg)
time (frames)

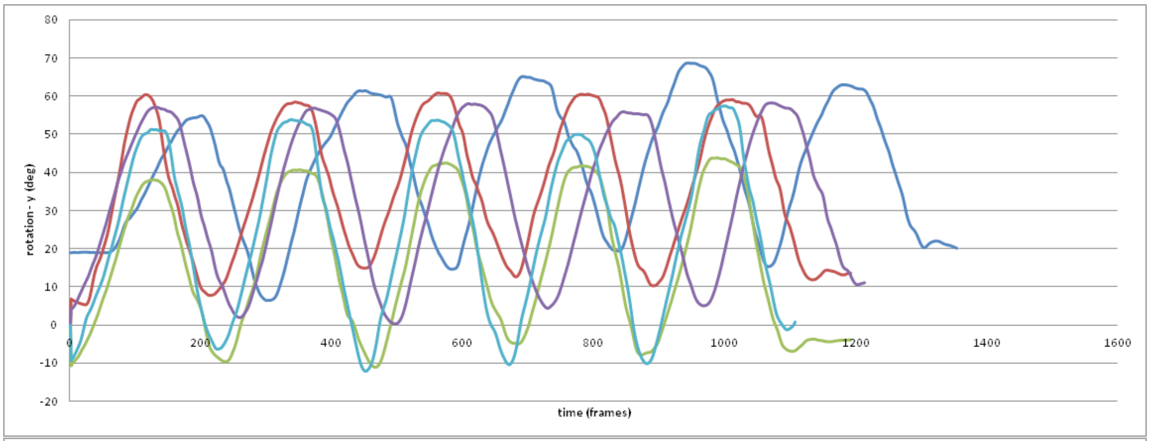

Flexion - right C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3


rotation - y (deg)
time (frames)

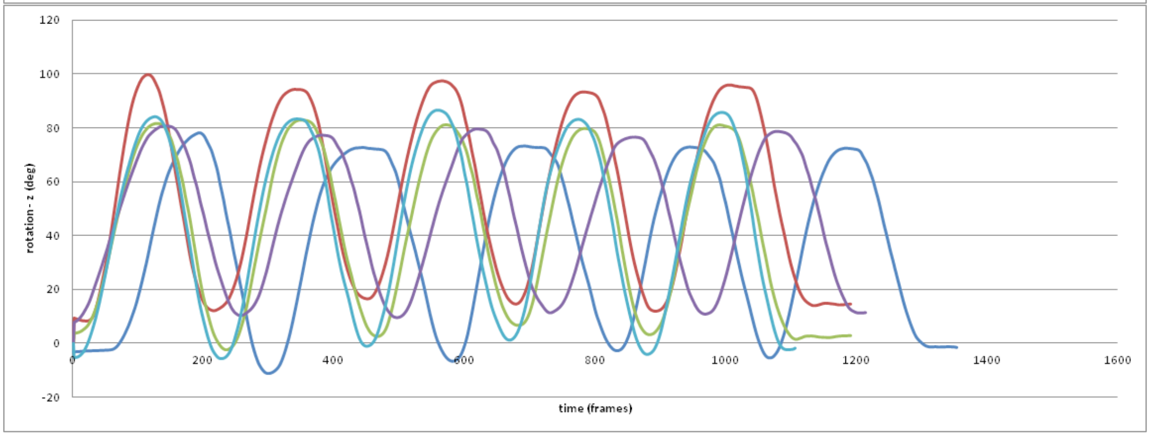

rotation - z (deg)
time (frames)


Flexion - left shoulder
rotation - x (deg)
rotation - y (deg)
rotation - z (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

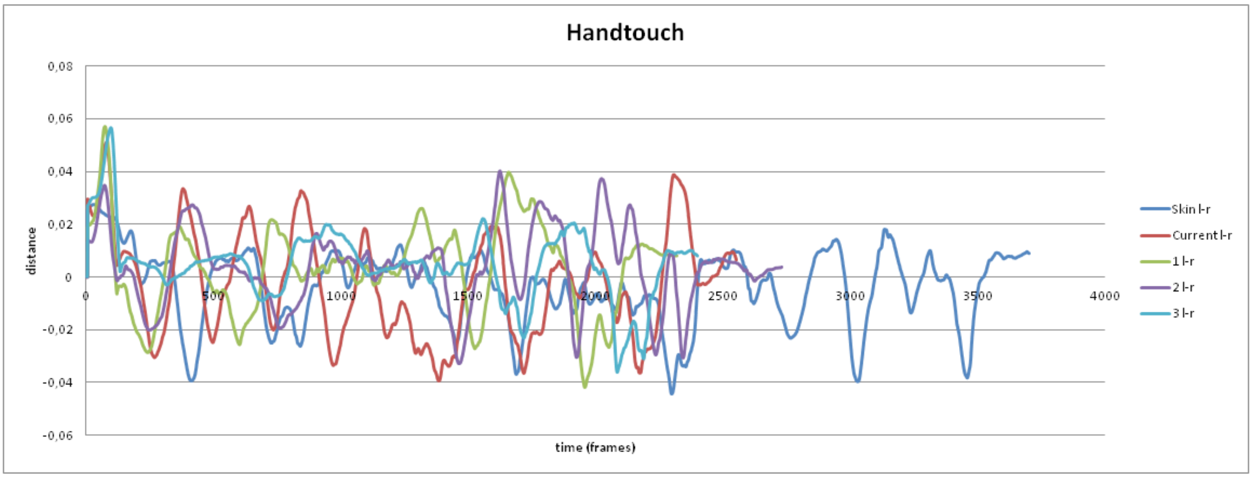

Flexion - right shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3



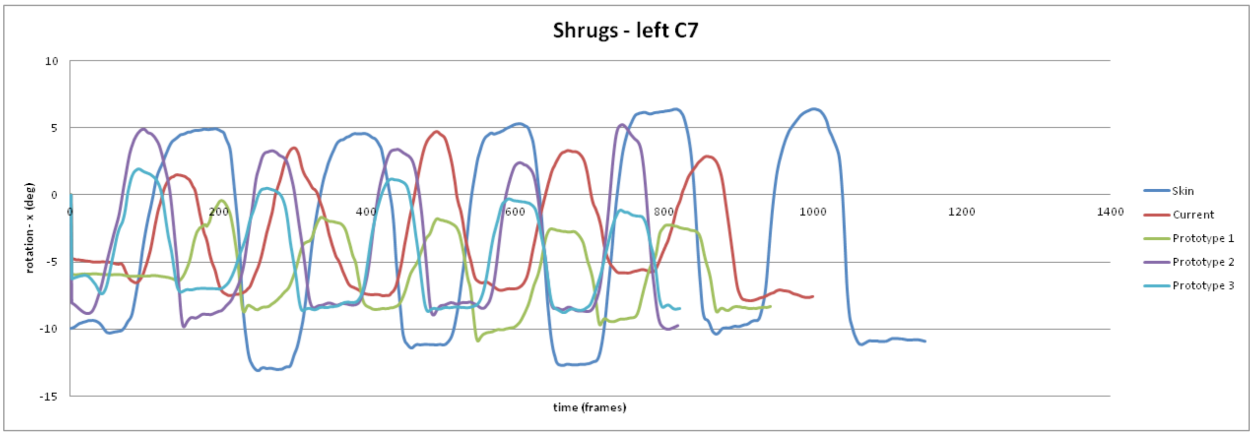
rotation - y (deg)
80
70
60
50
40
30
20
10
0
-10
-20
0
200
400
600
800
1000
1200
1400
1600
time (frames)



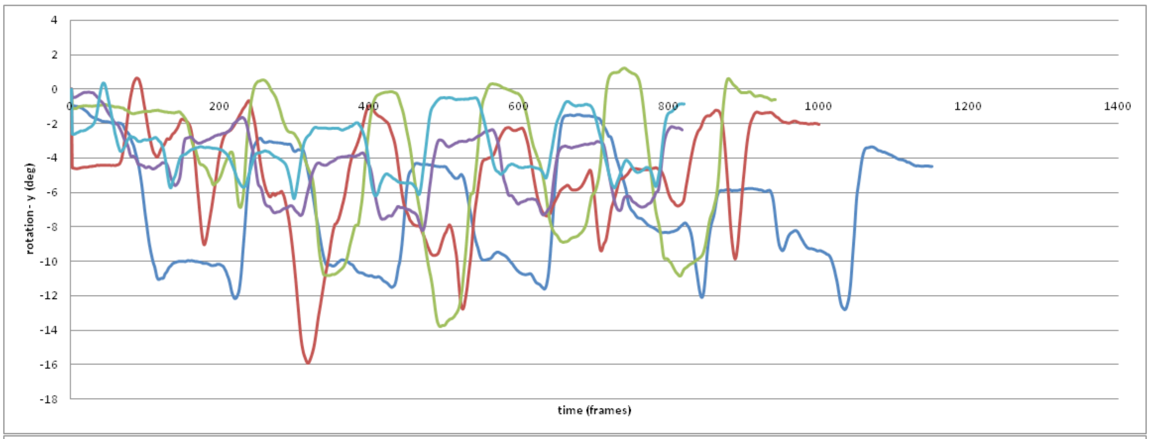
rotation - z (deg)
120
100
80
60
40
20
0
-20
0
200
400
600
800
1000
1200
1400
1600
time (frames)

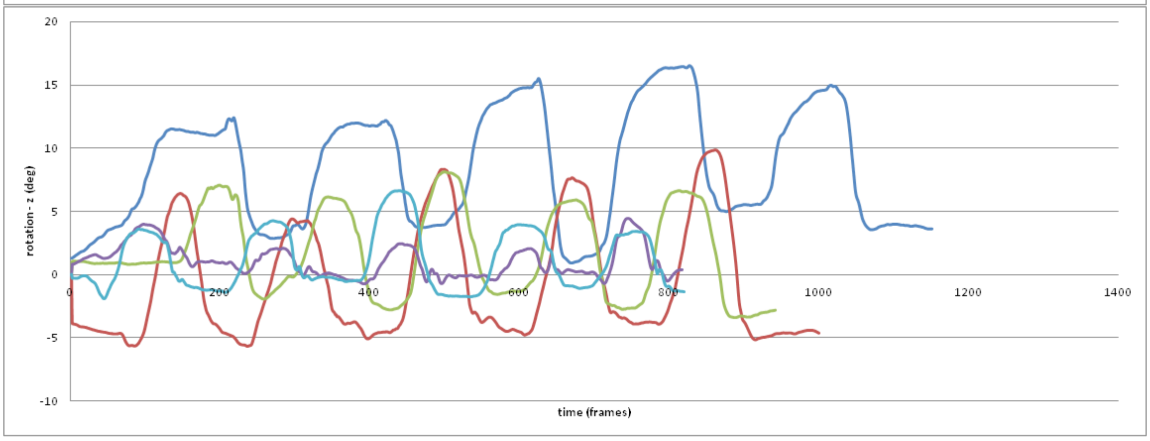


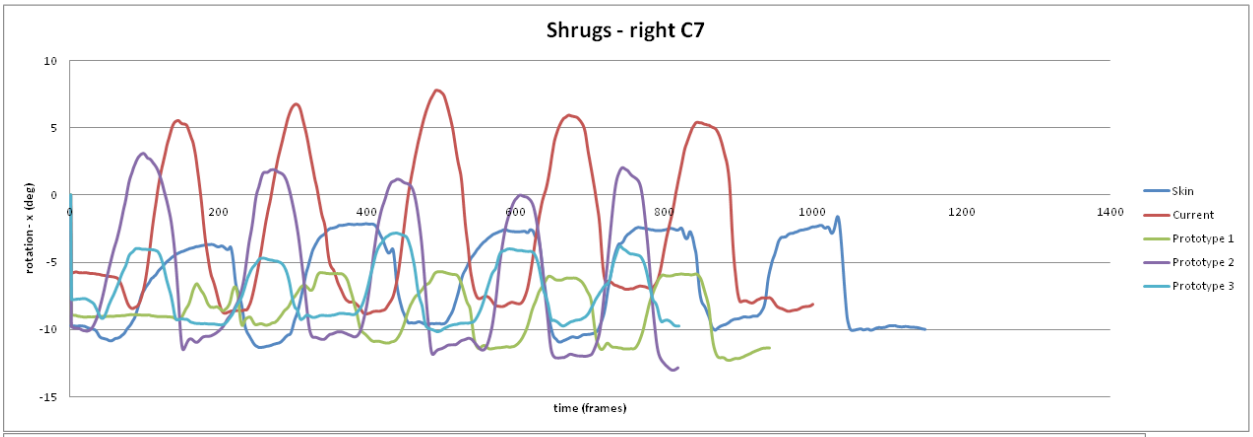
Handtouch
distance
0,08
0,06
0,04
0,02
0
-0,02
-0,04
-0,06
0
500
1000
1500
2000
2500
3000
3500
4000
time (frames)
Skin l-r
Current l-r
1 l-r
2 l-r
3 l-r

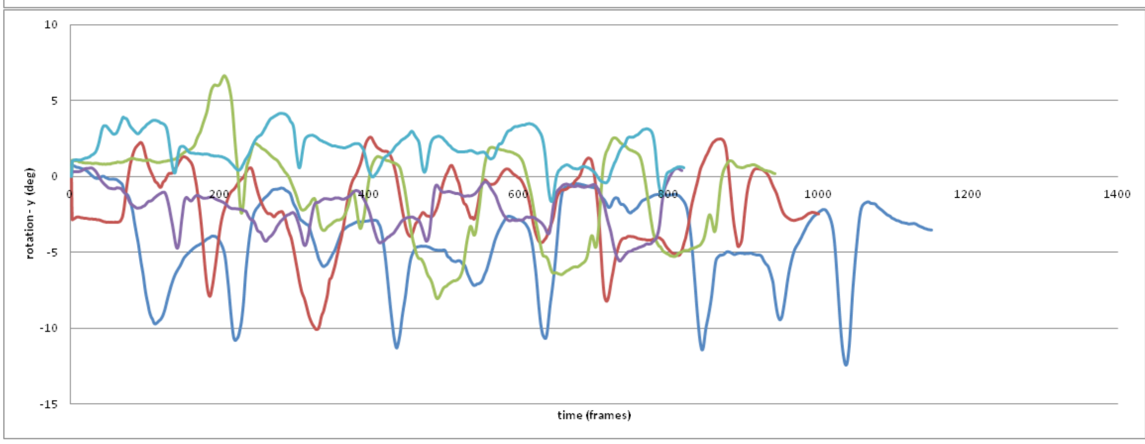


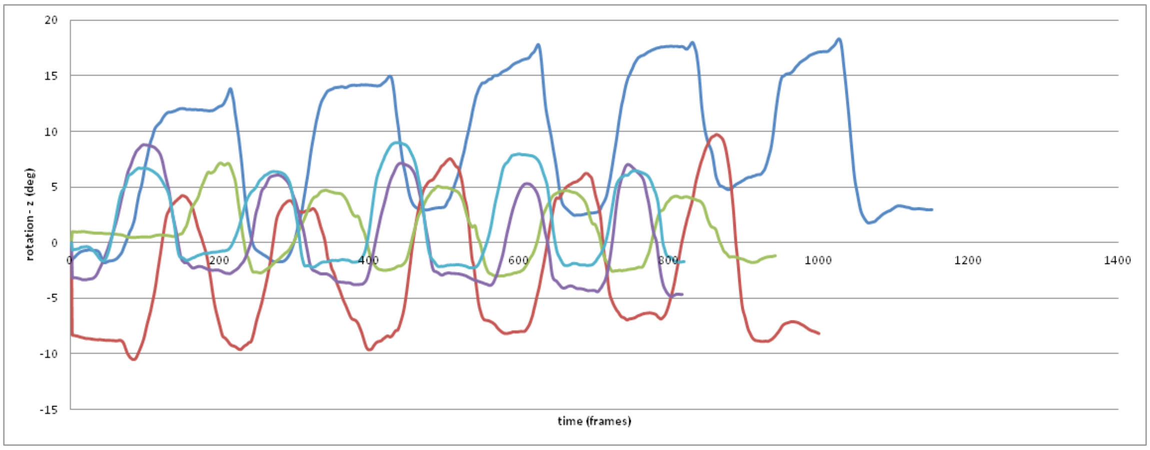
Shrugs - left C7
rotation - x (deg)
10
5
0
-5
-10
-15
0
200
400
600
800
1000
1200
1400
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3


rotation - y (deg)
time (frames)

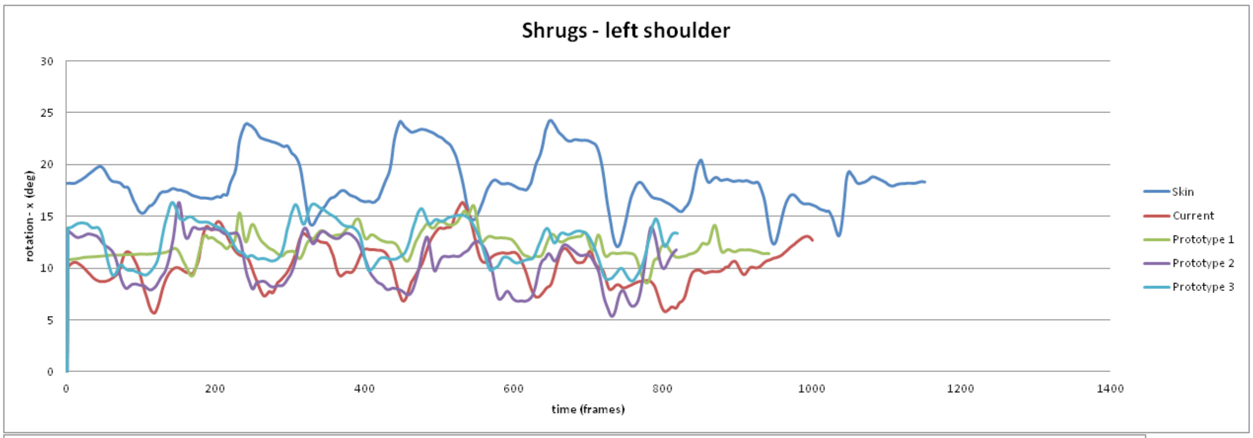

rotation - z (deg)
time (frames)


Shrugs - right C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

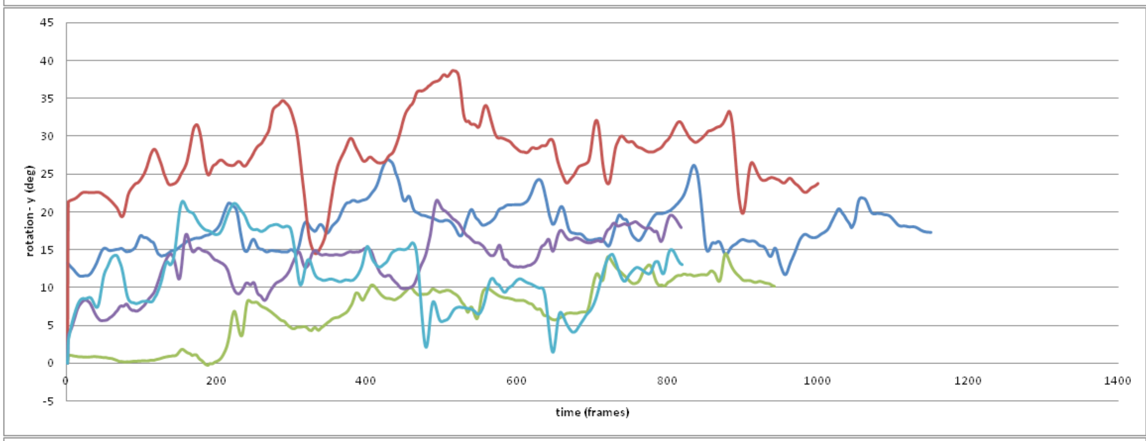

rotation - y (deg)
time (frames)



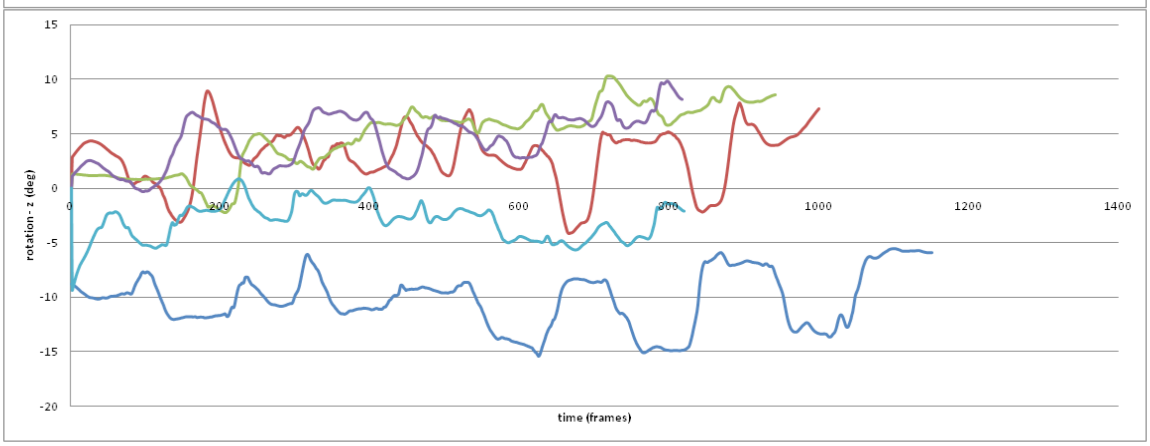
rotation - z (deg)
time (frames)



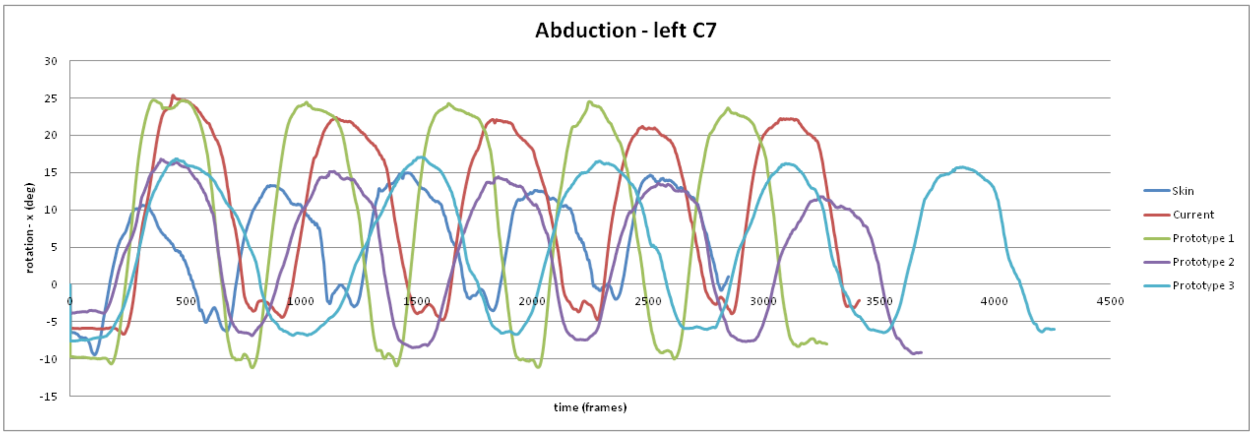
Shrugs - left shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3



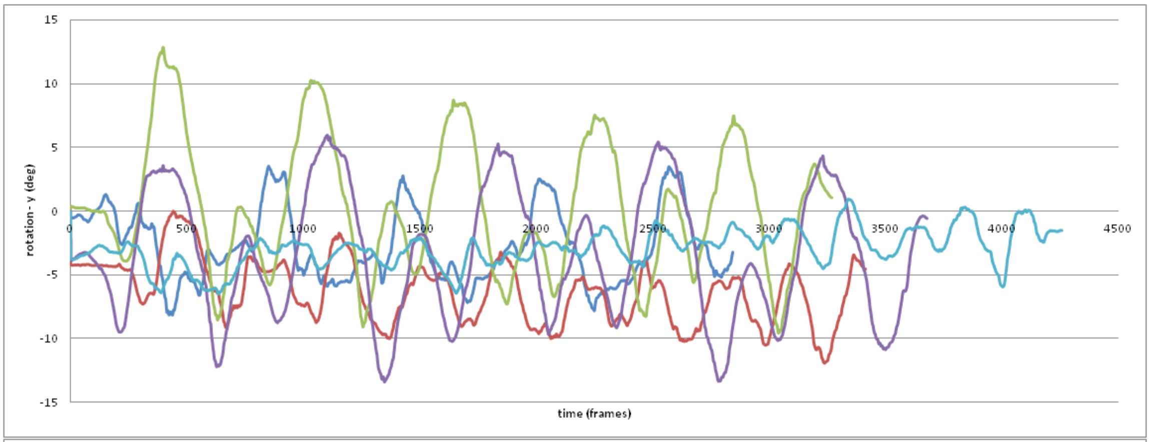
rotation - y (deg)
time (frames)

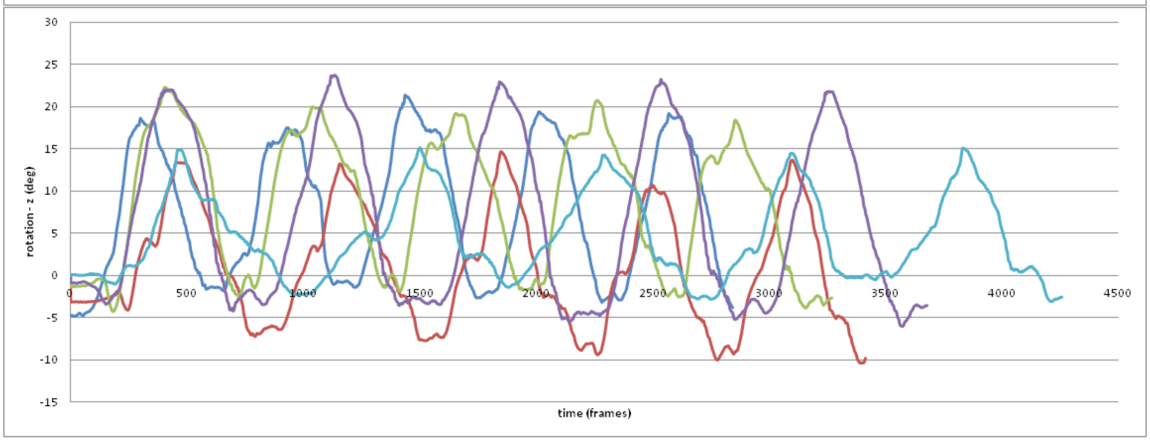


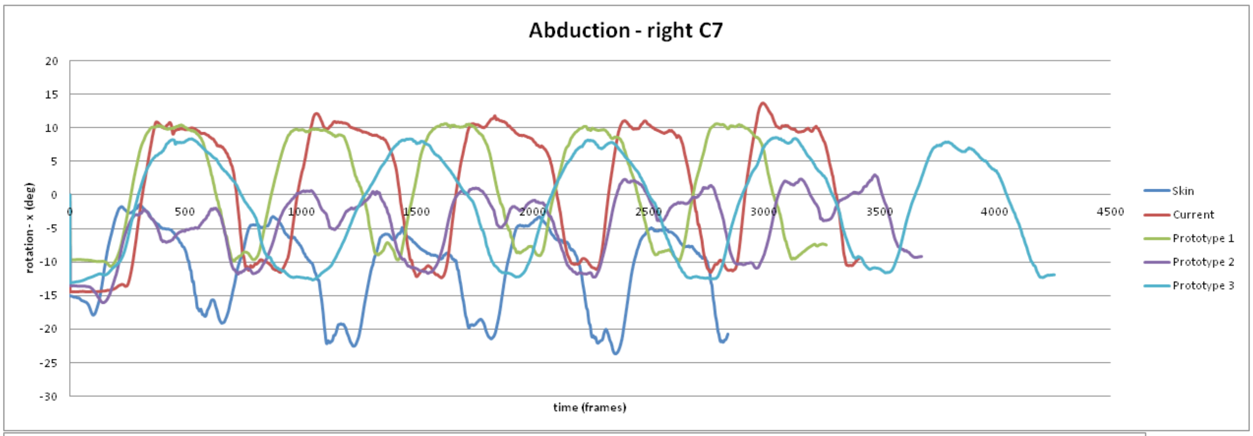
rotation - z (deg)
time (frames)

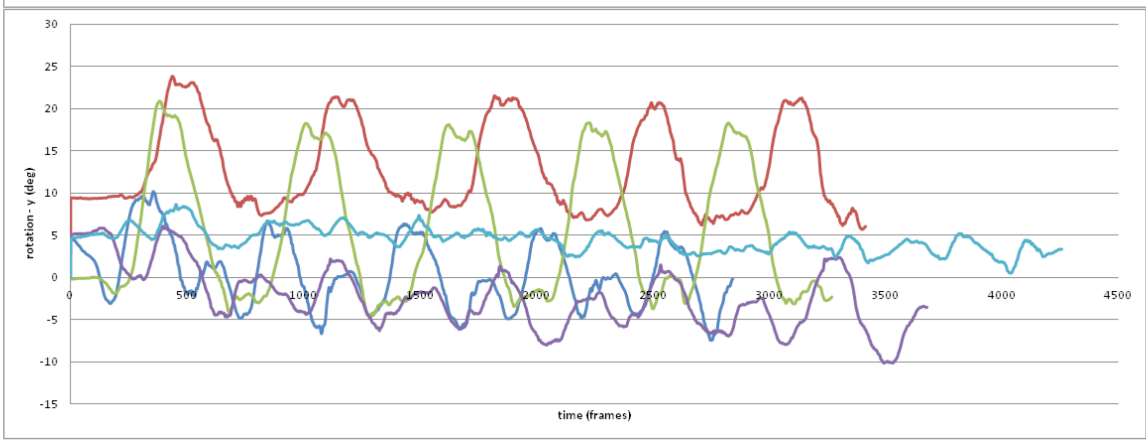


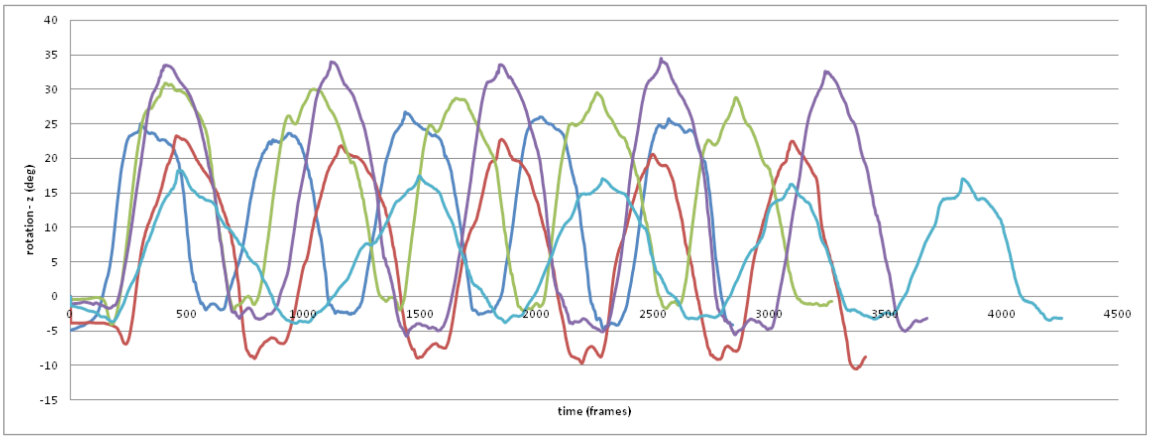
Participant 3

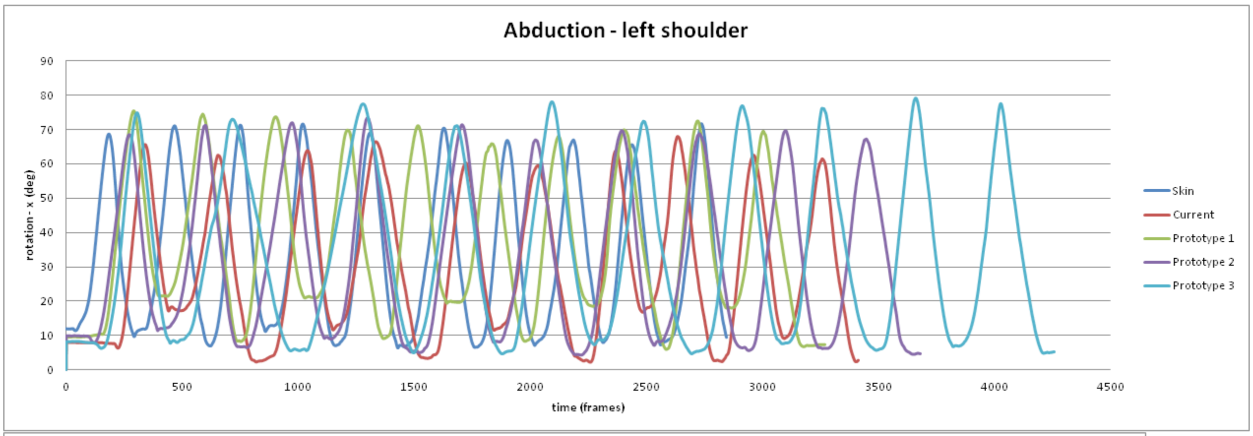

rotation - y (deg)
time (frames)
15
10
5
0
-5
-10
-15
0
500
1000
1500
2000
2500
3000
3500
4000
4500

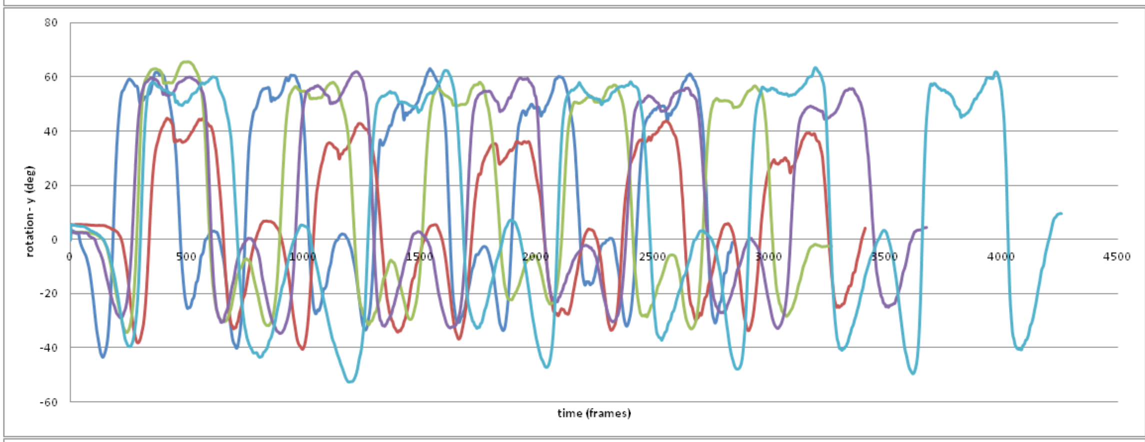

rotation - z (deg)
time (frames)
30
25
20
15
10
5
0
-5
-10
-15
500
1000
1500
2000
2500
3000
3500
4000
4500

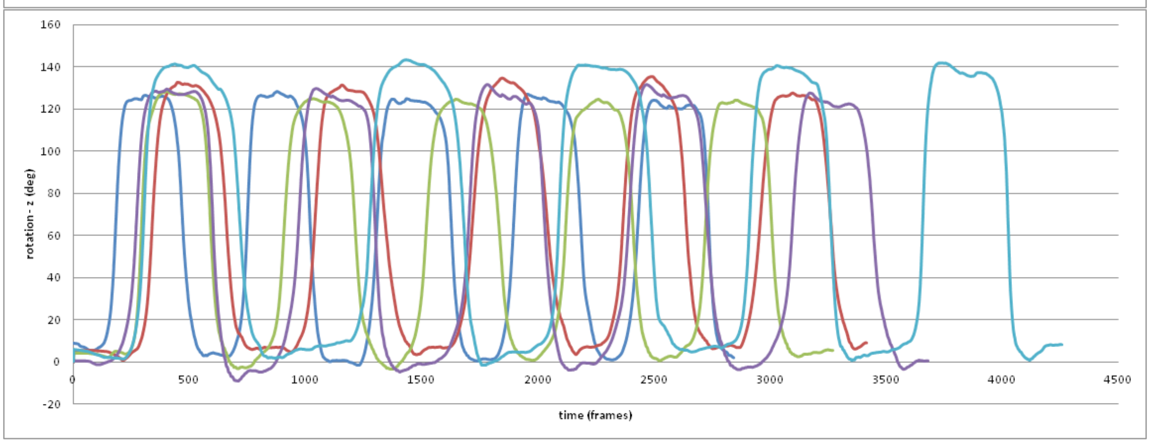

Abduction - right C7
rotation - x (deg)
time (frames)
20
15
10
5
0
-5
-10
-15
-20
-25
-30
500
1000
1500
2000
2500
3000
3500
4000
4500
Skin
Current
Prototype 1
Prototype 2
Prototype 3

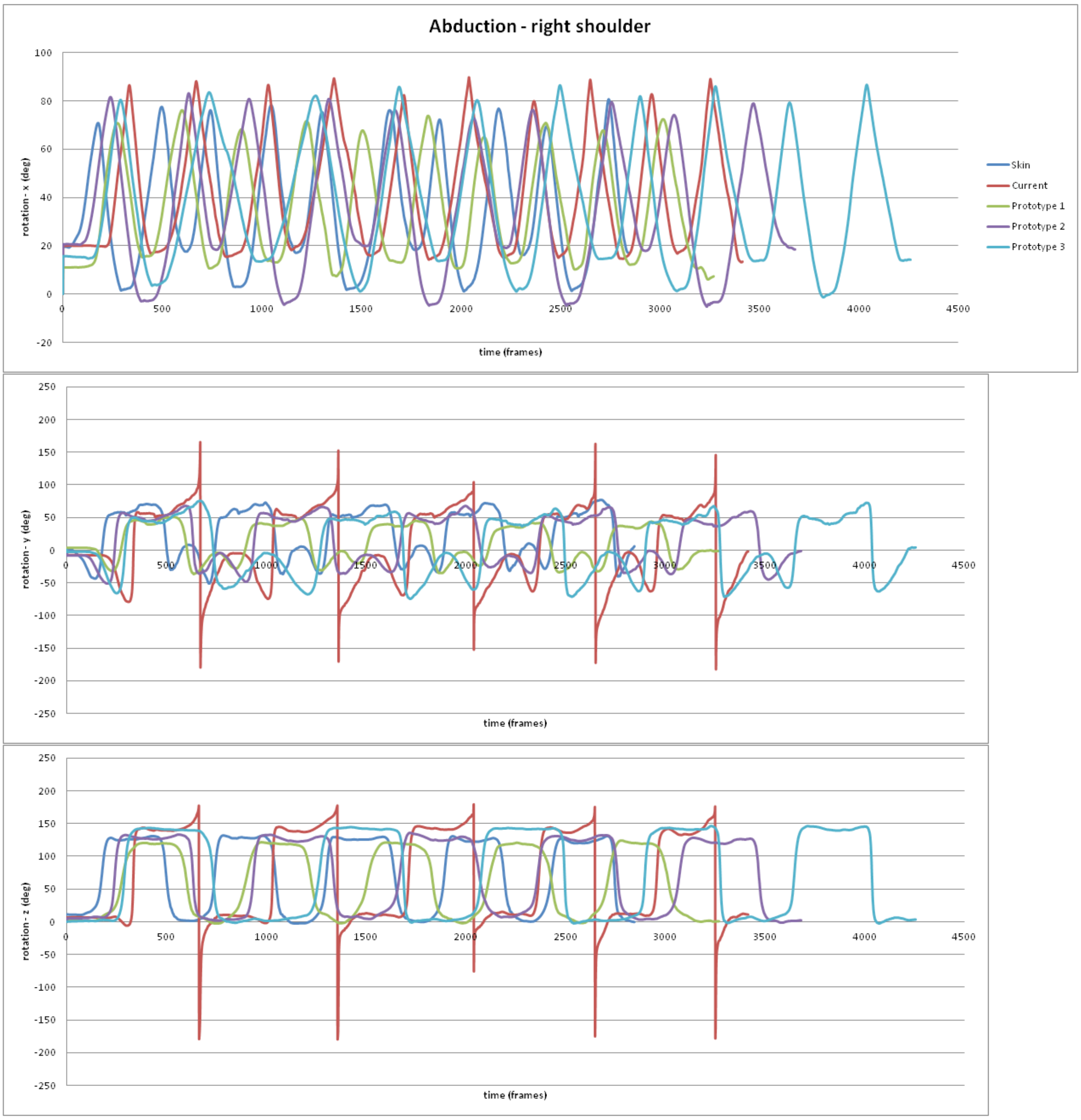

rotation - y (deg)
time (frames)
30
25
20
15
10
5
0
-5
-10
-15
0
500
1000
1500
2000
2500
3000
3500
4000
4500

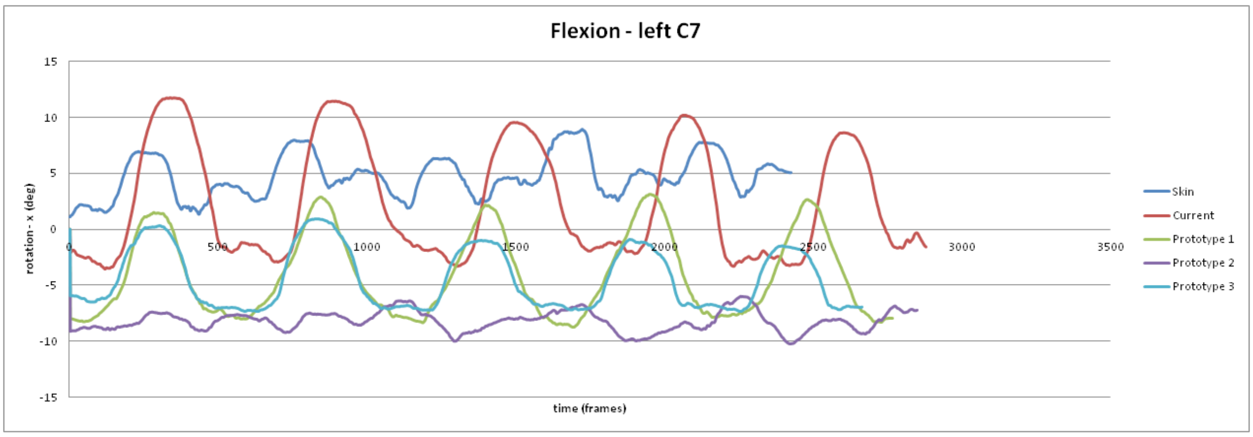

rotation - z (deg)
time (frames)

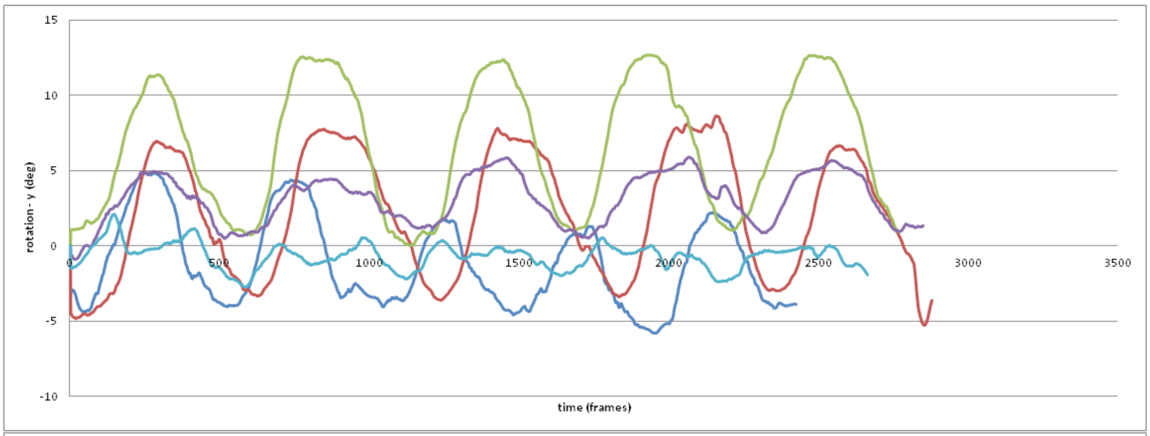

Abduction - left shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

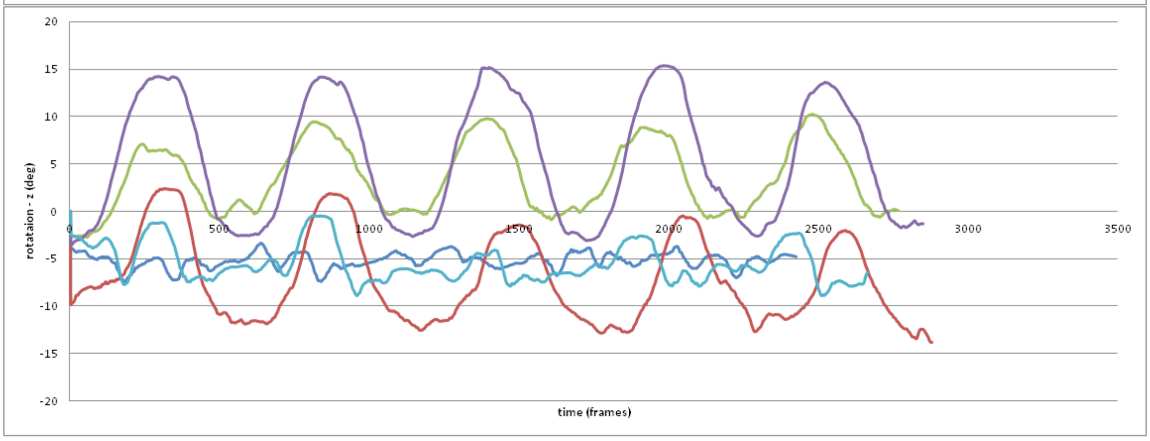

rotation - y (deg)
time (frames)

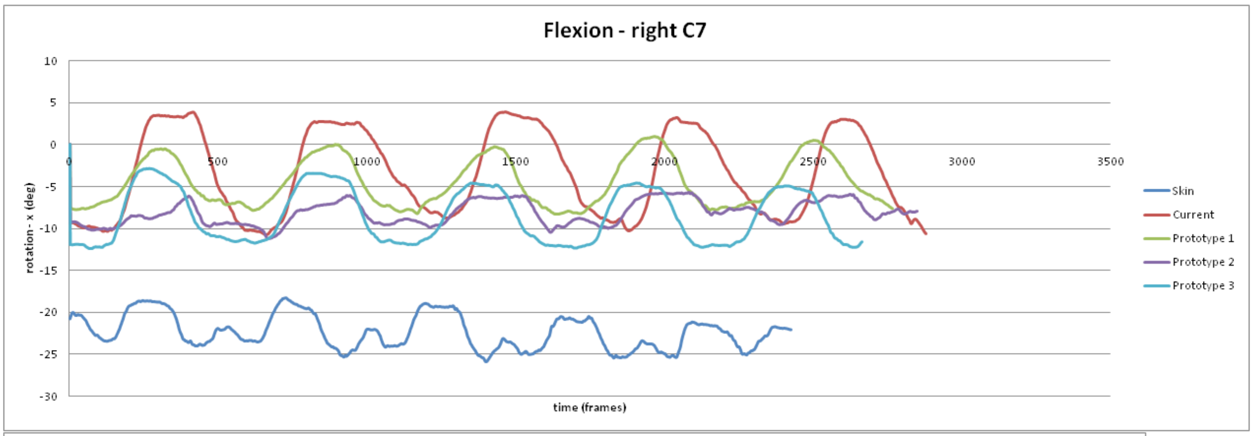

rotation - z (deg)
time (frames)

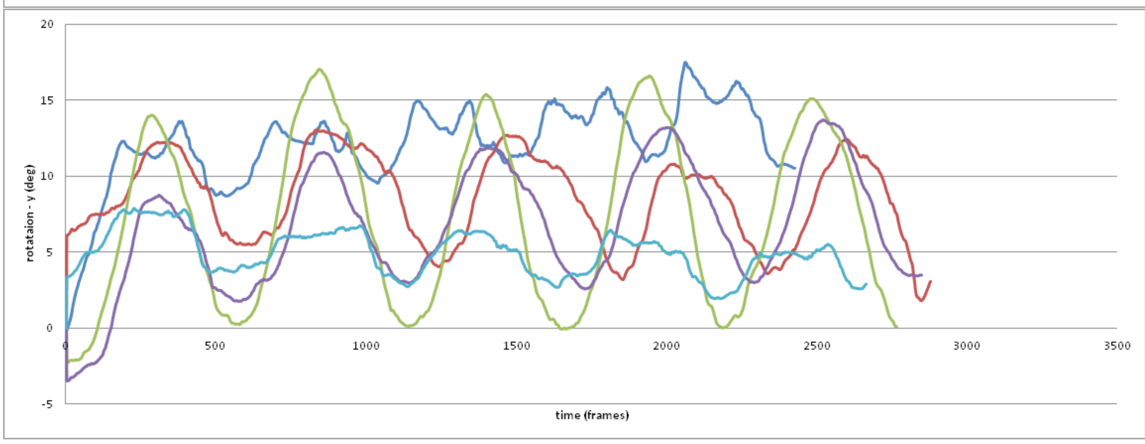

Abduction - right shoulder
rotation - x (deg)
rotation - y (deg)
rotation - z (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

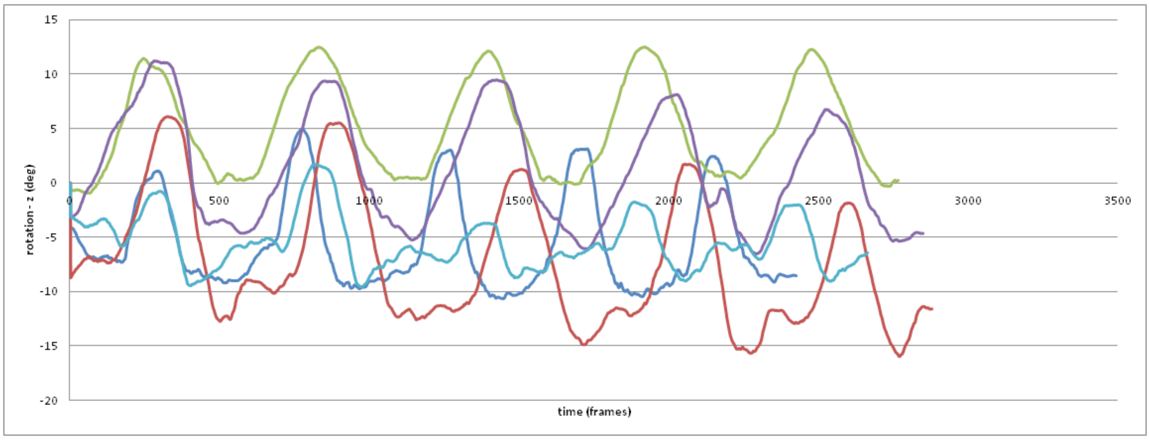

Flexion - left C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

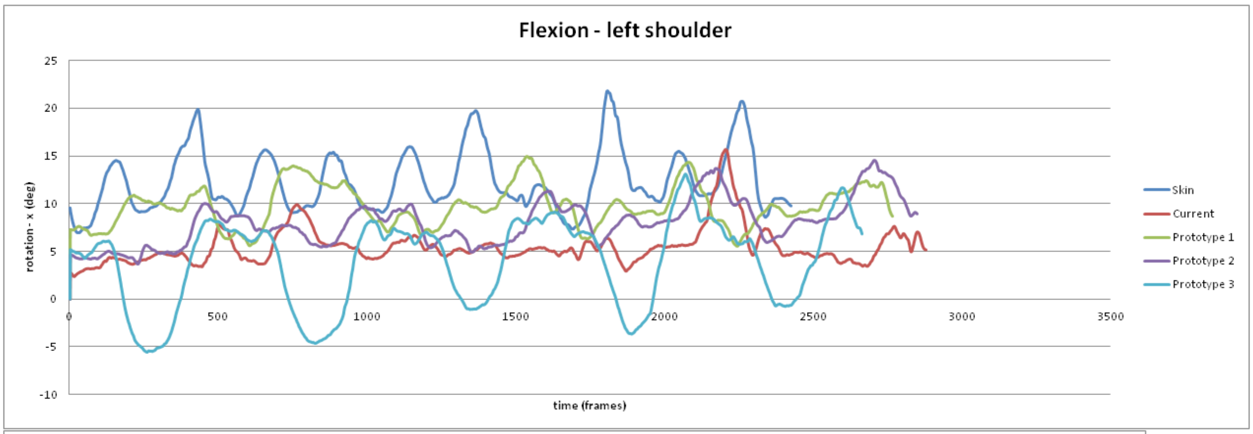

rotation - y (deg)
time (frames)

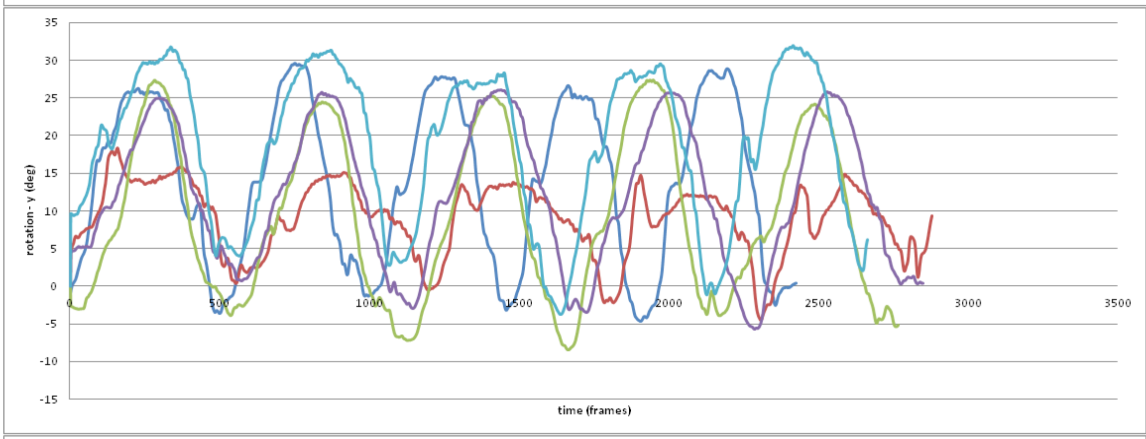

rotataion - z (deg)
time (frames)

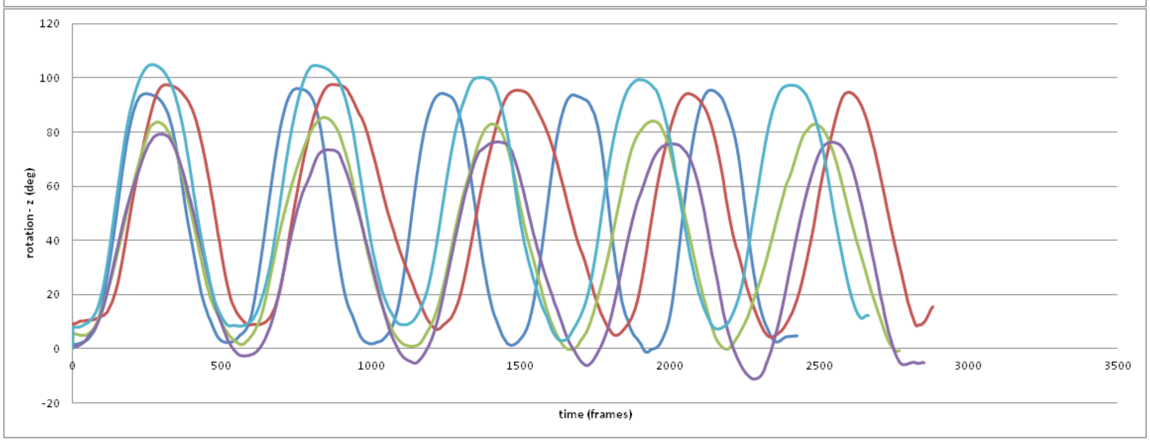

Flexion - right C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

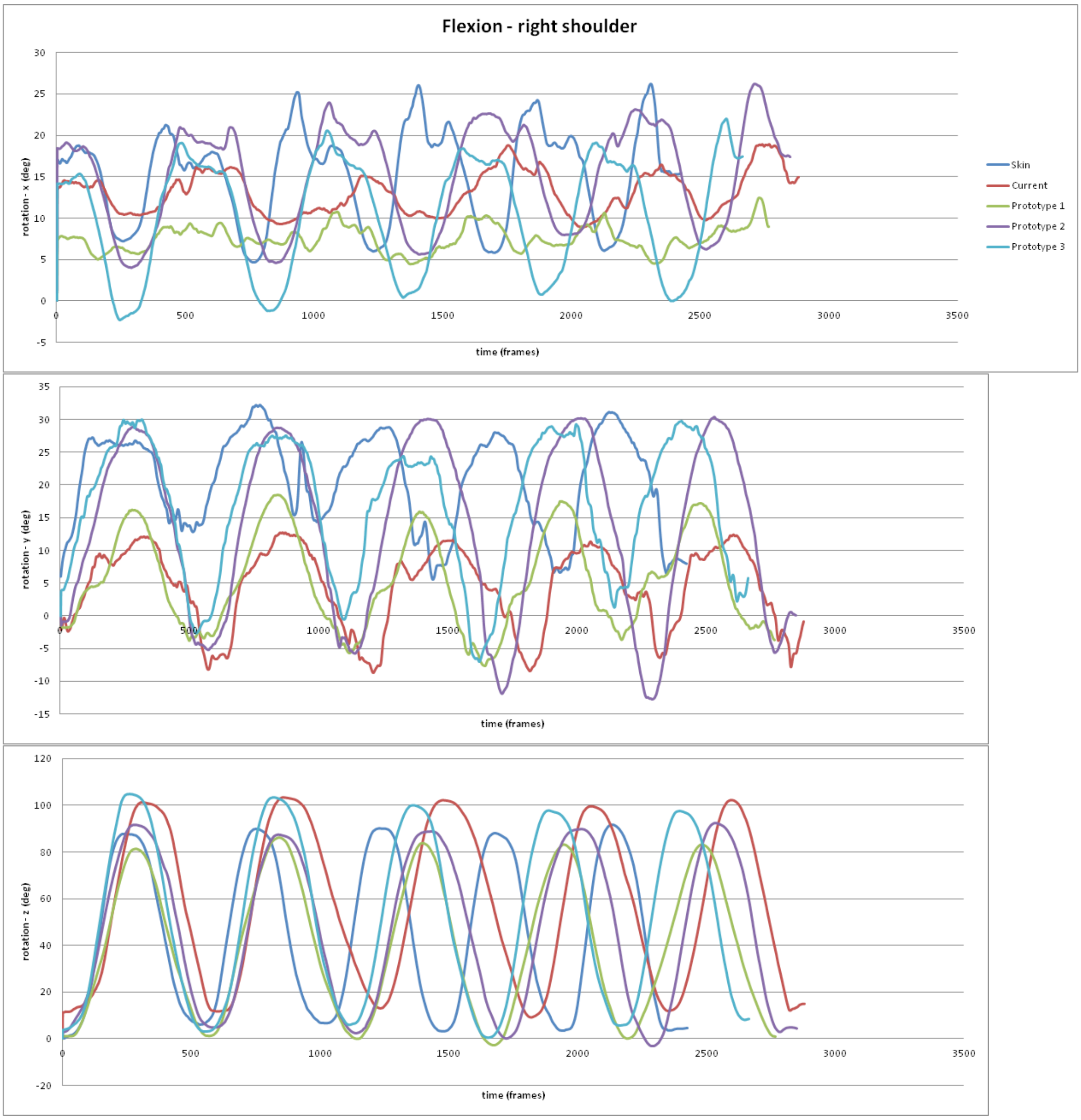

rotataion - y (deg)
time (frames)

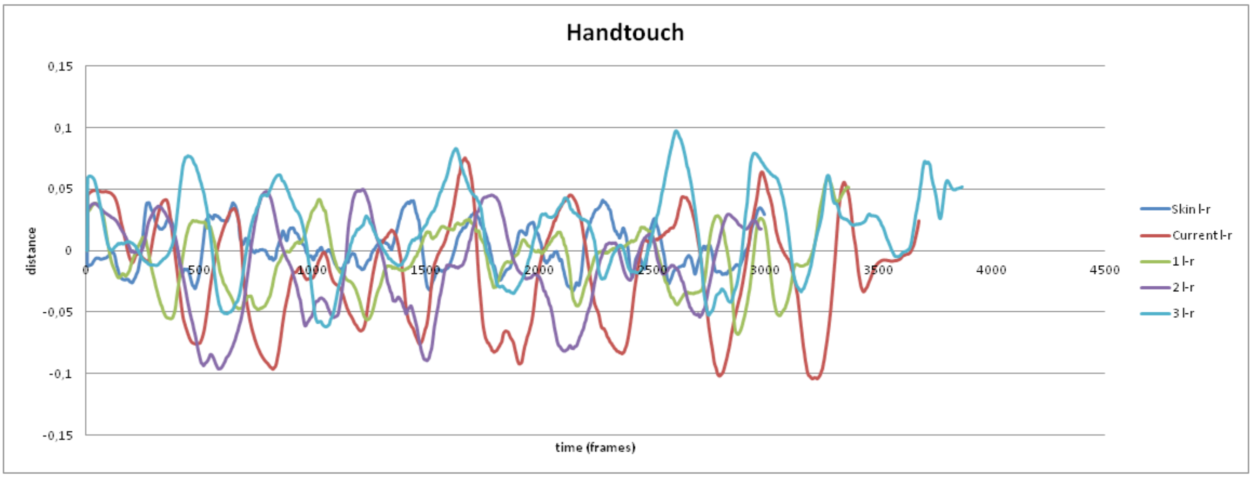

rotation - z (deg)
time (frames)

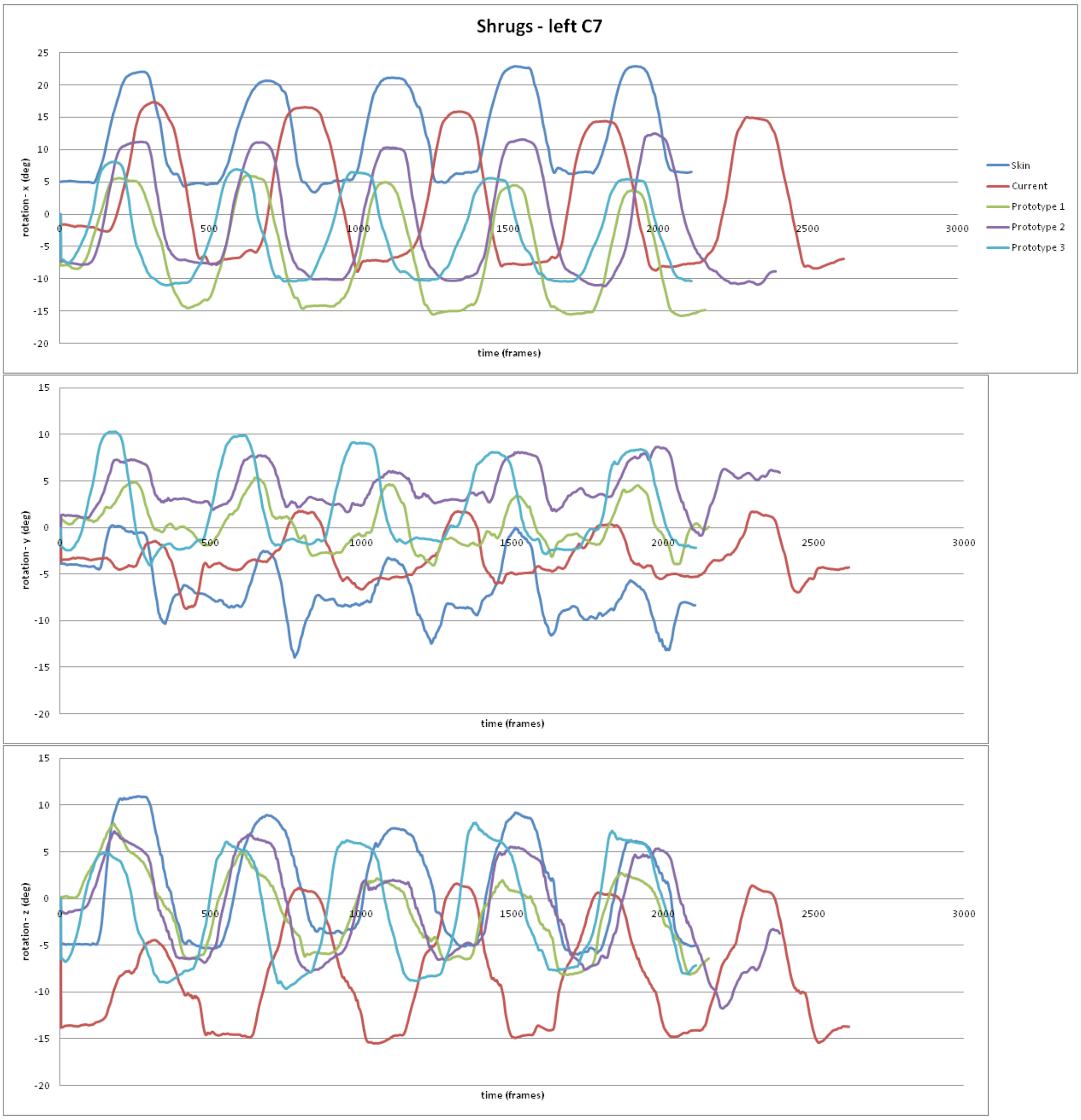

Flexion - left shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

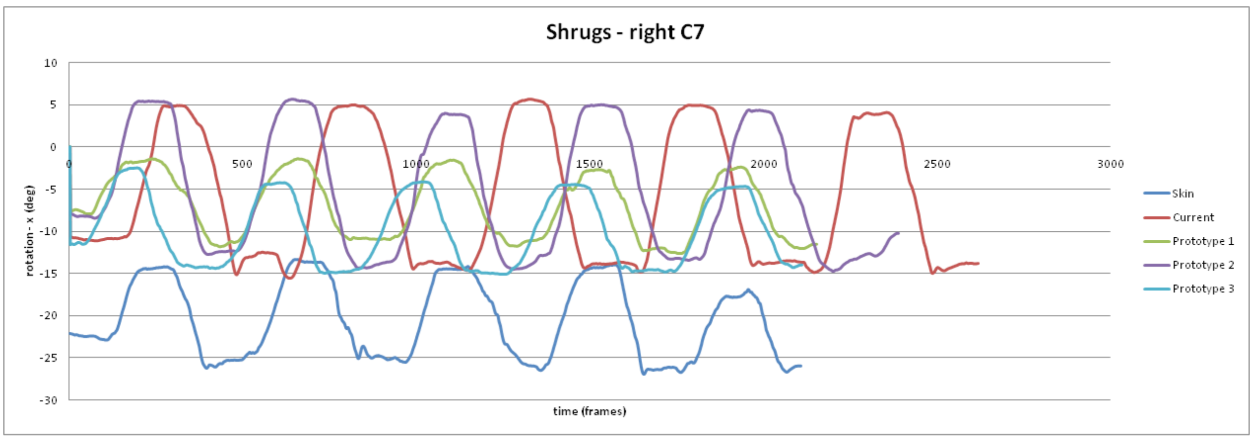

rotation - y (deg)
time (frames)

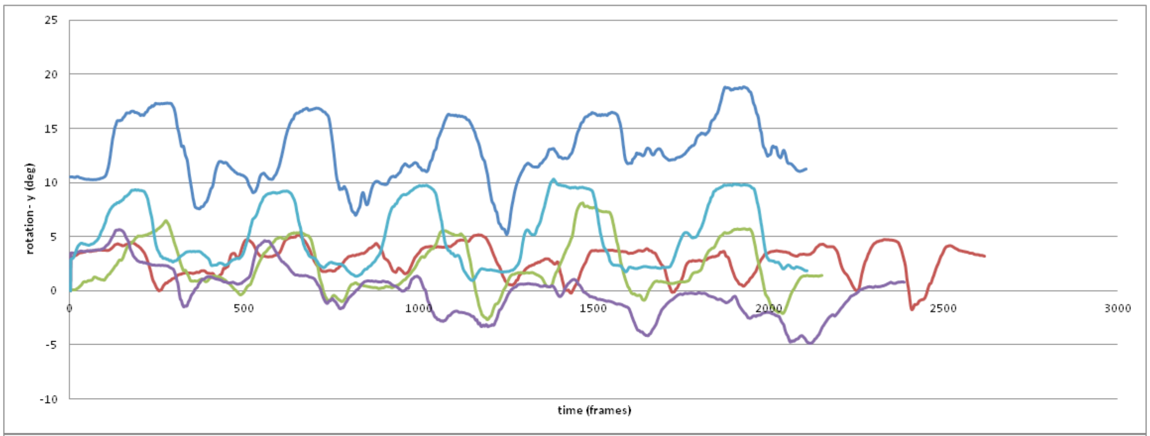

rotation - z (deg)
time (frames)

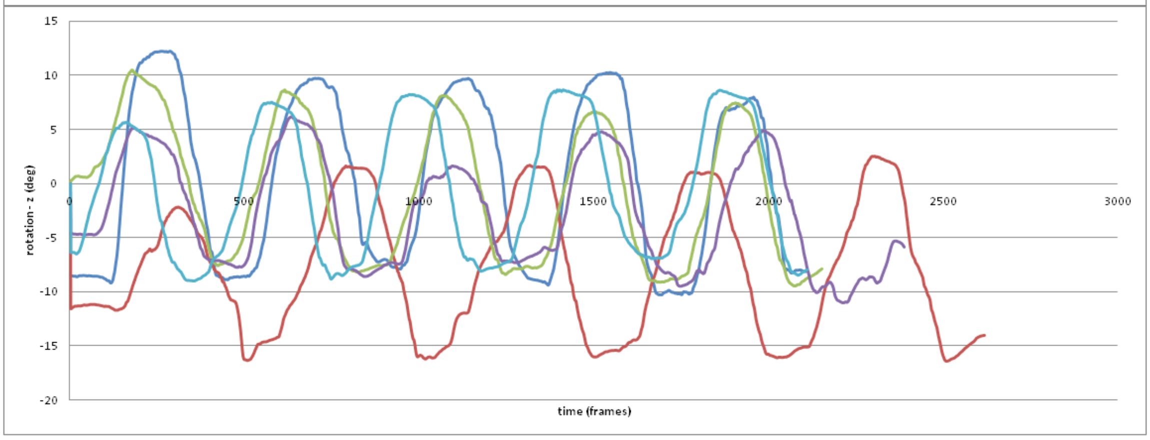

Flexion - right shoulder
rotation - x (deg)
rotation - y (deg)
rotation - z (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

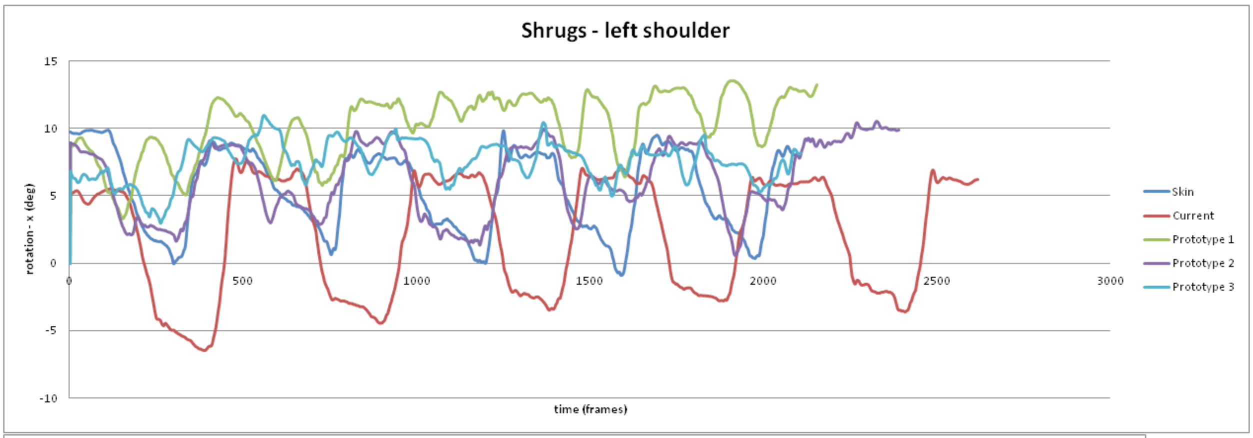

Handtouch
distance
time (frames)
Skin l-r
Current l-r
1 l-r
2 l-r
3 l-r

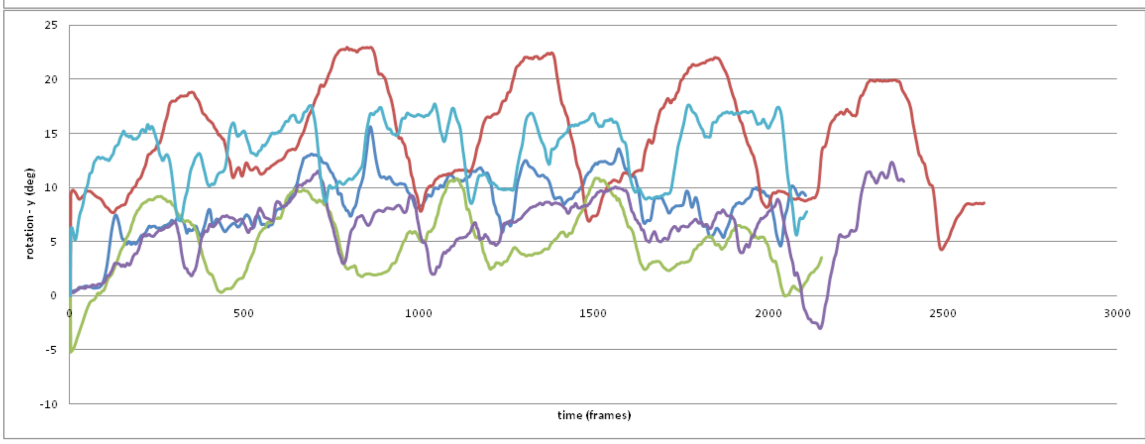

Shrugs - left C7
rotation - x (deg)
rotation - y (deg)
rotation - z (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

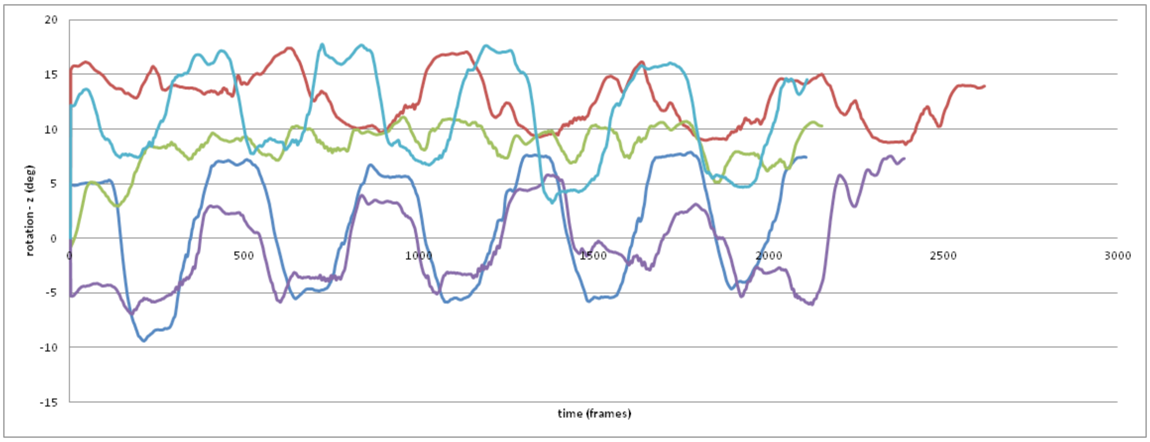

Shrugs - right C7
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3


rotation - y (deg)
time (frames)

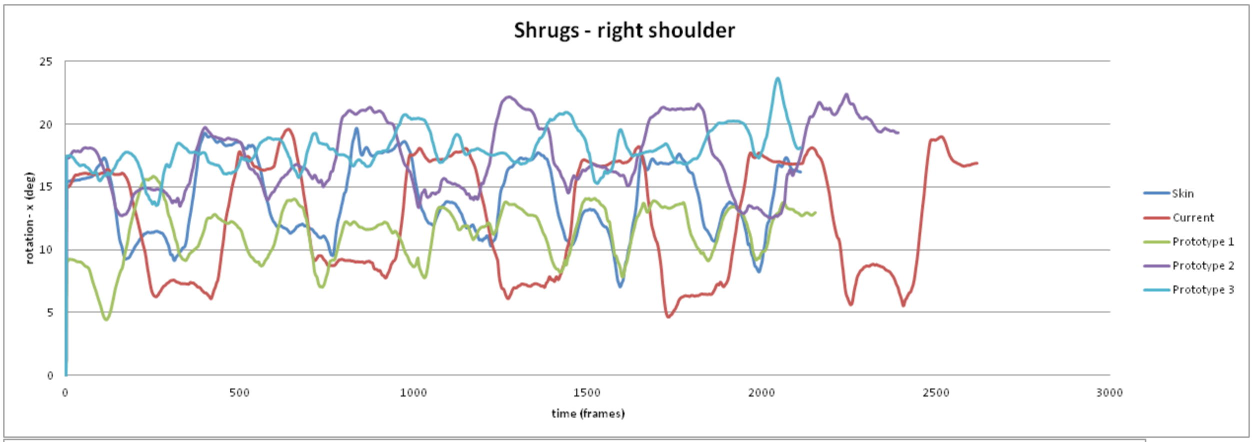

rotation - z (deg)
time (frames)


Shrugs - left shoulder
rotation - x (deg)
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3

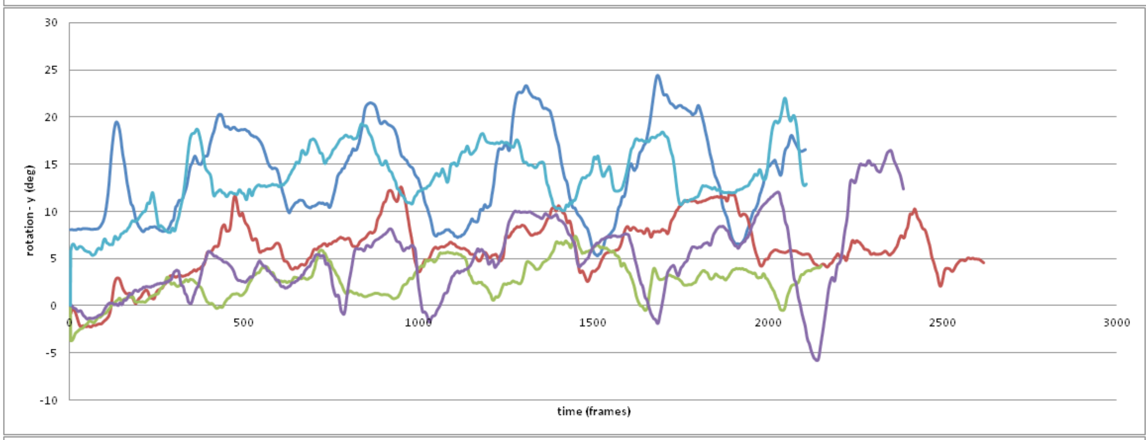

rotation - y (deg)
time (frames)



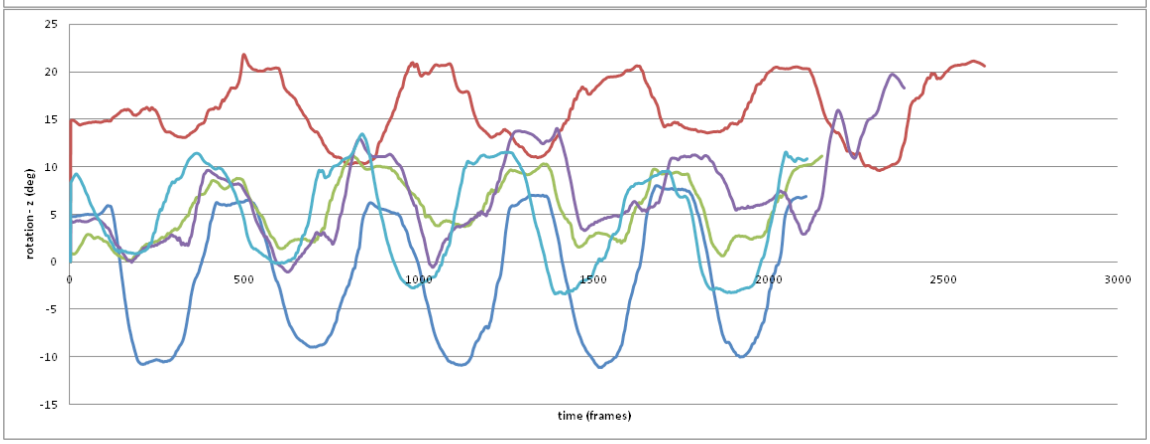
20
15
10
5
0
-5
-10
-15
rotation - z (deg)
0
500
1000
1500
2000
2500
3000
time (frames)



Shrugs - right shoulder
25
20
15
10
5
0
rotation - x (deg)
0
500
1000
1500
2000
2500
3000
time (frames)
Skin
Current
Prototype 1
Prototype 2
Prototype 3



30
25
20
15
10
5
0
-5
-10
rotation - y (deg)
0
500
1000
1500
2000
2500
3000
time (frames)



25
20
15
10
5
0
-5
-10
-15
rotation - z (deg)
0
500
1000
1500
2000
2500
3000
time (frames)