NOTES TO THE PRESENTATION

These are some notes to the presentation I had the opportunity to give during the ESMAC 2008 conference in Antalya, Turkey. As said, these are notes, so you might find some spelling or phrasing errors. Sorry for this and if you find them I would be glad to do the corrections, so please write me!

[INTRODUCTION]
Before entering into the details of the topic inertial and magnetic sensors and the upper-extremities, let me explain you why INAIL, the public institution for which I work, got so interested in this type of technology. INAIL is the Italian Workers' Compensation Authority.

[PROBLEM STATEMENT]
As such, we support Italian workers injured at the shoulder or elbow with rehabilitation and with an economic compensation roughly proportional to the impairment at the end of the treatment.

To enhance rehabilitation and to better quantify the compensation, it would be interesting for INAIL to diffuse to its local therapists' offices, quantitative motion analysis systems to objectively and quantitatively monitor the evolution of shoulder and elbow mobility.

The diffusion of traditional optoelectronic systems appears not feasible, for a number of reasons:

- A therapist office is generally a small room, while an optoelectronic system requires space for its installation to have good visibility
- The acquisition can be complicated by markers missing and occlusions, requiring a time-consuming post processing
- But, most of all, it is expensive!

[AIM AND CONTENT of the presentation]
For these reasons, at the INAIL Prostheses Centre we started a project to find the hardware and develop a protocol to allow the desired ambulatory assessment of shoulder and elbow 3D kinematics.

Today, I'll present you the hardware we chose, the protocol we developed plus some application scenarios.

[MATERIAL - HARDWARE]
Starting with the hardware, Inertial & Magnetic Measurement Systems were found to be a possible solution to overcome the limitations of optoelectronic systems. Different companies produce these technologies, but hereinafter I will only refer to the system we use, that is the MT9B, now MTx, developed by Xsens Technologies.

The MT9B consists of small sensors, these blue boxes (now orange and smaller), connected to a data logger. The data logger transmits the data from the sensors to a laptop via Bluetooth.
Each sensor integrate a 3D accelerometer, gyroscope and magnetometer. Since I'm not sure if all you are familiar with these sensors, here it is a quick summary.

Accelerometers and gyroscopes are usually referred to as Inertial sensors.

A 3D accelerometer is a chip which measures the accelerations of the body to which it is attached along 3 orthogonal axes. So, for instance, if the body is steady the acc measures along its axes the components of the gravity vector.
A 3D gyros, instead, is a chip which measures the angular velocity of the body to which it is attached, around three orthogonal axes. So, for example, if I attach a gyro to this pen and I start rotating it, the gyro will tell me: you are rotating the pan at 200° per second around this direction.
Finally, a magnetometer, is nothing more than a electronic compass, which tells us where the earth magnetic north is.

This said, what makes the MT9B sensors so interesting for motion analysis is that the information from the acc, gyro and magnetometer are combined through a Kalman filter, to provide, in real-time, the orientation of the coordinate system (CS) defined for each sensor with respect to a global coordinate system, based on the magnetic north and the gravity.
The sensor coordinate system is defined by the direction of the sensing axes of the acc, gyro and magnetometer and it is aligned with the boundaries of the box with an error of 3° in the worst case.

Put in other words, the output of an MT9B sensor is equivalent to the orientation of a cluster of markers relative to the global coordinate system of an optoelectronic system.

Apart from their small size, lightness and cost, MT9B sensors have a major advantage with respect to an optoelectronic system. Since the gravity and the north are ubiquitous and do not have to be created, the new sensing unit can measure the orientation of the body to which it is attached whenever and wherever you want, without the need of any camera or specially equipped lab. Your lab moves from a special room to the simple world. Or better, to your patient’s house, or to your medication room, or to the seaside. In other words the MT9B sensors satisfy the primary requirement of ambulatory measurement, that is “mobility”.

Or at least from the theoretical viewpoint. There can be a problem, which I think it is important for you to know immediately. Since the earth-based global coordinate system is based on the north, in the area where you are doing your measurements you must be sure that the north does not change direction or magnitude. If It does, the magnetometer will get dizzy, and will tell you that the body segment is moving while instead is the global coordinate system which is moving.
Variations in the direction and amplitude of the earth’s magnetic field can happen, for example, because you are near a metallic cupboard, desk, a DC motor, a car or because in your building there are big metal bars to sustain the floor.
To be honest, this problem is more relevant for gait analysis, because when walking you do move a lot. If you are interested in the upper-limb, you will not move that much. So just be sure to find a good spot with a stable magnetic field to do the measurement.
A simplified approach is the following. We can assume that if the direction of the magnetic field changes also the amplitude does. So grasp you sensor, activate only the magnetometer and move your arm within your arm workspace. If you see big variations, just find an other spot. If it is stable, you can proceed with the measurement.
Xsens is however continuously improving the tolerance of the system to variations of the magnetic field and they have a very strong research team. If you want to know the latest, ask them.

So now we know that if the environment is appropriate, the orientation of the MT9B sensors can be measured with respect to a global earth-based coordinate system. But this means that the MT9B sensors have the potential to measure joints kinematics.

[METHODS]
In fact, since the orientation of each sensor is known with respect to a global coordinate system, we can compute joint kinematics if:
1) a sensor is attached to each body-segment of interest;
2) at least one anatomical SoR (system of reference) is defined for each body-segment;
3) the orientation of the anatomical SoR is expressed in the SoR of the sensor;
Joints kinematics can be finally obtained from the relative orientation of the anatomical SoRs, according to the ISB recommendations.

And this is what we actually did. The problem, however, is that the MT9B does not provide you any information about the position of the sensors but only about the orientation. This means that we cannot use anymore the standard techniques based on the palpation of anatomical landmarks.

For this reason we developed a complete new protocol to compute the anatomical SoRs and relate them to the SoR of the sensors.
Before introducing you the steps of the protocol it is essential to make clear which is the underlying kinematic model we assumed for the upper-limb.

[UPPER-LIMB MODEL]
The upper-limb was assumed as an open kinematic chain formed by 4 segments (Thorax, scapula, humerus, and forearm) and three joints (scapulothoracic joint, glenohumeral joint and elbow).
The scapulothoracic and glenohumeral joint were assumed as a ball & socket joint described by three independent rotations. A system of reference is then required for thorax, scapula and humerus to describe the kinematics of these joints.
The elbow was modelled as double hinge joint with the FLEX and PS axes constant and non intersecting. To measure the elbow kinematics, therefore, two systems of reference must be defined: one for the distal humerus and one for the forearm. Following standard conventions used in mechanics, the coordinate system for the humerus should have the X axis alongside the FLEX axis, Z perpendicular to the long axis of the humerus and X, and the Y consequently. The forearm coordinate system shoulder have Y along the PS axis, Z entering into the wrist and the X consequently. If the relative orientation of the forearm and distal humerus coordinate systems are decompose using the Euler xz’y’’ convention we can measure the flex, carry-angle and ps angle. Please note that with this model, the carrying angle becomes a constant parameters, subject specific, describing the rotation of the FLEX axis with respect to the long axis of the humerus.

In conclusion, therefore, the model requires the definition of 5 anatomical SoR: one for the thorax, scapula and forearm and 2 for the humerus.

[PROTOCOL – SENSORS ON BODY]
The protocol for the definition of these 5 SoRs was based on three steps:
1) position the sensors over the subject’s body following few simple rules;
2) measure the sensors orientation with the subject standing still
3) measure the sensors orientation while the subject performs one pure flexion-extension and one pure prono-supination of the elbow.
But let’s start with Step 1.

[STEP 1 – sensor POSITIONING]
The sensors were positioned as follows:
1) For the thorax, the sensor is positioned over the flat portion of the sternum, with its Z axis away from the body. It doesn't matter if the sensor is rotated.

2) For the scapula, the X of the sensor is aligned with the cranial edge of the scapula's spine, over the central third of the scapula.
3) For the humerus the sensor is just positioned and oriented to minimize the soft-tissue artefact: usually over the central third of the humerus, slightly posterior.
4) For the forearm, the base of the sensor is positioned over the distal, flat surface of radius and ulna, with its Z axis pointing away from the wrist.

[STEP 2 – STATIC ACQUISITION]
After sensor placement, the orientation of the sensor is measured while the subject stands still, back straight, with the arm alongside the body, perpendicular to the ground. We than pick a frame out of the acquisition and we compute the anatomical SoR for thorax, scapula and proximal humerus:
1) the thorax SoR has the **Y** axis is along gravity; the **X** perpendicular to gravity and the Z axis of the sensor. The **Z** consequently**.**
2) the scapula SoR has the X along the axis of the sensor (so along the scapula's spine). The Z perpendicular to X and the gravity and Y consequently
3) the proximal humerus SoR is just a copy of the SoR of the thorax

[STEP 3 – FLEX PS]
After the static acquisition, we measure the orientation of the sensors over humerus and forearm while the subject flexes and extends the elbow, cyclically, keeping a constant prono-supination. From this trial, applying the method proposed by Woltring it is then possible to compute the elbow FLEX axis. We can then compute the SoR of the distal humerus following the steps I showed you before.
By repeating the same steps during a pure elbow prono-supination, we can compute the orientation of the PS axis of rotation in the SoR of the sensor on the forearm. We can then compute the forearm coordinate systems as follows: the Y axis along the PS axis, the X is the cross product of the Y and the sensor Z axis and the Z consequently.

[STEP 4 – DYNAMIC COMPUTATION]
Once completed the placement, the static trial and the pure flexion-extension and PS, the orientation of the anatomical SoRs is known in the SoRs of the sensors. This means that, during a dynamic task, the change in orientation of the sensors will make the anatomical SoRs to change. The relative orientation of the anatomical SoRs will then provide the joints/segments kinematics.

[PROS AND CONS OF THE PROTOCOL]
Now, before continuing let's try to draw some conclusions about the protocol.

- The protocol requires a very simple placement of the sensors on the subject, really unambiguous. From about 20 patients acquired so far I can state that in 5-10 minutes you can execute the full protocol and get ready for measuring some clinically relevant activity.
- the definition of the anatomical SoRs is subject-specific and the SoRs were defined as closely as possible to the ISB recommendations;
- the SoRs for the distal humerus and forearm guarantee the optimal description of the elbow kinematics;
- and finally, the problem: all sensors are skin-mounted, so the soft tissue artefact can cause underestimations in the ranges of motion. The good news, however, is that the problem is the same that has to be faced when you use skin mounted markers, so the recommendations are the same.

To solve the problem of the underestimation of the humerus and forearm axial rotations, I suggest you to have a look at these two papers, which advanced two possible solutions.

About the underestimation of scapula rotations, well, here the things get tricky. On some patients the underestimation will not be that much. For example for this subject measured with the protocol, the scapulo-humeral rhythm (that is the coordination between humerus flexion or ab-adduction and scapula-medio lateral rotation) is quite consistent with the literature. But for other subjects, instead, there could be underestimations. For example the flat range of this pattern here is a little more than what you would expect. The accuracy you can get due to the sensor's position can depend on the muscles, fatness and quality of the skin. The relevance of the problem, however, really depends on what is your clinical question. If you are mostly interested in intra-subject comparison, this is no longer a big issue as long as the system remains sensitive enough to the pathologies and it is reliable inter and intra-rater. If you are interested in inter-subject comparison, instead, accuracy is an issue and a possible solution is to use the protocol as it is, but instead of attaching the sensor over the skin, you could attach it to a scapula locator, as the one shown here. With the scapula-locator, however, you can only do static acquisition. So you have to face a trade off, which depends on your application! I can now tell you our application and show you two videos.

[VIDEO 1]
We basically have two scenarios. Both involve people in their working-age, who underwent surgery for purely orthopaedic pathologies at the shoulder. Both use the measure of the scapulo-humeral rhythm and RoM as primary reference measures, since both are important clinical parameters for these patients.

So here it is the video of the first scenario.
This is a patient with a sound side, while the other is under rehabilitation. We performed the protocol and we asked him to do a pure shoulder flexion with his sound side. Here you can see his scapulo-humeral rhythm plotted in real-time. From it we computed a reference band, and here you can see the movement performed again and you can appreciate how repeatable can be the measurement. Now we ask him to repeat the same activity but with the affected side. And you can know see the difference in the kinematic pattern. With the system and the protocol you can immediately see the difference between the affected and the sound side. But you can do something more. You can let the patient see the video and you can ask him to follow his own sound side pattern with the affected side, as an exercise. Of you can put your hands on the patient and teach him what to do, both having a tangible reference under to look at. The system with the protocol moves from being a measurement tool to a rehabilitation support with a video biofeedback.

And here is a second scenario. I have to thank Dr. Giuseppe Porcellini from Cervesi Hospital in Cattolica for his support in this clinical application. The patient was surgically treated for a sovraspinatus + SLAP lesion, and we filmed him during the rehabilitation. The physiotherapist wanted to see the difference between the patient's scapulo-humeral rhythm in three different conditions:
1) when the patient was performing a flexion-extension of the shoulder on his own
2) when performing it being actively guided
3) when continuing on his own the gesture as taught by the physio by following the scapulo-humeral rhythm measured during 2.

And here are the results of the pattern. The pattern when the subject did the movements alone (in red) is substantially different from the one when the physio was guiding the movement (here in green). This could instead be closely replicated by the subject following the training and the video-biofeedback offered by the system.

At the end of the tests, the physio was very happy of the protocol's outcome, because it was the first time he could see in real-time the scapulo-humeral rhythm of the subject. And he could see that the pattern alone was different from the one he was trying to teach to the subject. It was also helpful for the patient, who could exercise himself with a clear visible reference.

I think that the possibility for the physio to put his hands on the patient during the measurement and practice with the subject with a visible reference could open new interesting perspective in the rehabilitation of shoulder orthopedic pathologies.

From another viewpoint, this is also an example of the good sensitivity of the system to changes in the motor performances of the subjects.

In both scenarios the comparison was within subject, if not within session. In these conditions we are not that afraid of the underestimation of the scapula medio-lateral rotation again, as long as the system and protocol is reliable and sensible enough.

[OPEN QUESTIONS]
If I were you are this point of my presentation I would have in mind at least some of these questions:
1) given the protocol, which is the accuracy of the MT9B when used to measure the upper-limb kinematics in comparison with a Vicon?
2) are the anatomical coordinate systems we defined representative of the actual joint kinematics?
3) which is the inter and intra-subject reliability of the protocol?
4) which kind of activities will you ask you subjects to do?

Some of the answers can be found in the papers we published in Medical and Biological Engineering and Computing. For the others, you can always get in touch with me writing to ag.cutti@inail.it

[CONCLUSIONS]
Trying to conclude, I might say that when the system and protocol will be completely validated, they have the potential to 1) allow the ambulatory measurement of shoulder and elbow kinematics and 2) to be not just measurement tools but a real support for rehabilitation exercises.