SHOULDER FUNCTION AND OUTCOME EVALUATION AFTER SURGERY USING 3D INERTIAL SENSORS

THÈSE N° 3870 (2007)

PRESENTEE LE 12 JUILLET 2007

FACULTÉ SCIENCE ET TECHNIQUES DE L'INGÉNIEUR

Laboratoire de mesure et d'analyse des mouvements

SECTION DE GÉNIE ÉLECTRIQUE ET ÉLECTRONIQUE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

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Lausanne, EPFL
2007

Abstract

The importance of outcome evaluation of a medical treatment in orthopedics is currently recognized. In shoulder disease, a large variety of evaluation tools is employed to assess the results of the surgery. However, even if the majority of these evaluations are largely widespread, none was accepted as a universal standard. Since 1990, few researchers have been evaluating the assumption that the movement analysis (with camera-based or electromagnetic systems) is likely to provide objective results. In clinical practice, these techniques are not always applicable for outcome evaluation of a treatment. The surgeons lack a convenient and simple method of evaluating in an objective way a patient's activity and quality of life after a surgery of the shoulder.

This project provides a new tool for the objective functional evaluation of shoulder pathologies, a tool that can be easily used by a doctor at a hospital and by the patient at home. It allows the measurement of the biodynamic changes as well as 3D kinematics of the treated shoulder by noting the effects of these changes on clinical results and on the patient's daily activity.

The project was split in four complementary studies. In the first study, a new ambulatory device allowing long-term monitoring of the shoulder movement using several inertial sensors (3D gyroscopes, 3D accelerometers) attached on the trunk, the humerus and the scapula's spine was designed. By combining acceleration and angular velocity features of the both humerus during 9 tests, three kinematic scores for the functional assessment of the shoulder were presented to evaluate the shoulder function in patient before and after surgery. The kinematic scores objectively showed the shoulder improvement after surgery.

In the second study, a new method was proposed to detect and quantify the dominant upper-limb segment during daily activity. The method was tested on healthy subjects (N=31) and a patient group (N=10, at baseline, 3, 6 and 12 months after surgery) while carrying the system during 8 hours of their daily life. The results showed the dominance of the arm during standing, sitting and walking periods for healthy subjects and the

quantification of the shoulder improvement after surgery, by taking into account the presence of the disease in the dominant or the non dominant arm.
In the third study, 3D gyroscopes attached on the humerus were used to identify the movements of flexion-extension, abduction-adduction and internal/external rotation of the humerus and to identify the rates of adjunct (deliberate rotation) and conjunct rotations (inherent or automatic rotation) within each movement. The frequencies of each movement (number/hour) for the different ranges of the arm speed, as well as the rate of adjunct and conjunct rotations for each movement were estimated during daily activity in healthy and patient groups. The results provided the values of frequency of each movement and adjunct/conjunct rate based on the data obtained from the healthy group. In the pathological case, we found that the painful dominant shoulder of the patients lost its predominance in favor of the healthy shoulder, the non dominant shoulder. Patients had less pure internal/external rotations and performed less fast movements while after surgery these parameters presented no significant differences with the healthy group.
In the fourth study, a new method of detecting the working level of the shoulder was presented. By measuring the arm elevation during motionless periods, we proposed a new score to evaluate the ability of working at a specific level for a definite duration. We showed that this score had an average of 100% (±31%) for healthy subjects while the working level of the painful shoulder was lower than the healthy shoulder and improved significantly after surgery (up to 87% at 6 months).

This study provides preliminary evidence of the effectiveness of the proposed system in clinical practice and objectively assesses upper-limb activity during daily activity.

Keywords: *Ambulatory system, Outcome evaluation, Shoulder functionality, Upper-limb.*

Résumé

L'importance de l'évaluation de résultats d'un traitement médical dans l'orthopédie est actuellement reconnue. Dans les maladies de l'épaule, une grande variété d'outils d'évaluation sont utilisés pour évaluer les résultats de la chirurgie. Cependant, même si la majorité de ces évaluations est en grande partie répandue, aucune n'a été acceptée comme norme universelle. Depuis 1990, peu de chercheurs avaient évalué l'hypothèse que les systèmes (basés sur des caméras ou les systèmes électromagnétiques) de l'analyse de mouvement sont susceptibles de fournir des résultats objectifs. Dans la pratique clinique, ces techniques ne sont pas toujours applicables pour l'évaluation des résultats d'un traitement. Les médecins manquent d'une méthode pratique et simple pour évaluer de façon objective l'activité et la qualité de vie d'un patient après une chirurgie de l'épaule.

Ce projet fournit un nouvel outil pour l'évaluation fonctionnelle objective des pathologies de l'épaule, un outil qui peut être facilement employé par un docteur dans un hôpital et par le patient à la maison. Il permet la mesure des changements de biodynamique comme la cinématique 3D de l'épaule traitée en notant les effets de ces changements sur des résultats cliniques et sur l'activité quotidienne du patient.

Le projet a été séparé en quatre études complémentaires. Dans la première étude, un nouveau dispositif ambulatoire, permettant la surveillance à long terme du mouvement de l'épaule à l'aide de plusieurs capteurs inertiels (gyroscopes 3D, accéléromètres 3D) attachées sur le tronc, l'humérus et la partie supérieure de l'épine de l'omoplate (acromion), a été conçu. En combinant les accélérations et les vitesses angulaires de l'humérus pendant 9 tests, trois scores cinématiques pour l'évaluation fonctionnelle de l'épaule ont été présentés pour évaluer la fonction de l'épaule avant et après chirurgie. Les scores cinématiques ont montré objectivement l'amélioration de l'épaule après chirurgie.

Dans la deuxième étude, nous avons proposé une nouvelle méthode pour détecter et mesurer le segment dominant des membres supérieurs pendant l'activité quotidienne. La méthode a été examinée sur les sujets en bonne santé (N=31) et un groupe patient (N=10, baseline, 3, 6 et 12 mois après chirurgie) tout en portant le système pendant 8 heures de leur vie quotidienne. Les résultats ont montré la dominance du bras pendant des périodes debout, assis et de marche pour les sujets en bonne santé et la quantification de l'amélioration de l’épaule après chirurgie en tenant compte de la présence de la maladie dans le bras dominant ou non dominant.

Dans la troisième étude, les gyroscopes 3D attachés sur l'humérus ont été utilisés pour identifier les mouvements de flexion-extension, l'abduction-adduction et les rotations internes et externes de l'humérus et pour identifier dans chaque mouvement les taux de rotations adjointes (rotation délibérée) et de rotations conjointes (rotation inhérente ou automatique). La fréquence de chaque mouvement (nombre/heure) pour les différentes gammes de la vitesse de bras, comme le taux de rotations adjointes et conjointes pour chaque mouvement, a été estimé pendant l'activité quotidienne dans le groupe contrôle et les patients. Les résultats ont fourni les valeurs de la fréquence de chaque mouvement et les taux conjoints/adjoints basés sur les données obtenues à partir du groupe contrôle. Dans les cas pathologiques, nous avons constaté que l’épaule dominante et lésée des patients, a perdu sa prédominance en faveur de l'épaule saine, l'épaule non dominante. Ils ont eu moins de rotations internes et externes pures et exécutent moins de mouvements rapides tandis qu'après chirurgie, ces paramètres n'ont présenté aucune différence significative avec le groupe contrôle.

Dans la quatrième étude, une nouvelle méthode pour détecter le niveau de travail de l'épaule a été présentée. En mesurant l'altitude du bras pendant des périodes immobiles, nous avons proposé un nouveau score pour évaluer la capacité de travailler à un niveau spécifique pour une durée définie. Ce score a eu une moyenne de 100% (±31%) pour les sujets en bonne santé tandis que le niveau de travail de l'épaule douloureuse était inférieur à l'épaule saine et a été amélioré sensiblement après chirurgie (plus de 87% à 6 mois).

Cette étude fournit l'évidence préliminaire de l'efficacité du système proposé dans la pratique clinique et pour évaluer objectivement l'activité des membres supérieurs pendant l'activité quotidienne.

Keywords: *Système ambulatoire, Evaluation des résultats, Epaule, Membres supérieurs.*

Acknowledgements

I would like to express all my gratitude and sympathy to Professor K. Aminian Head of the Laboratory of Movement Analysis and Measurement for giving me the opportunity to work in the research pf biomechanics and human movement analysis, for his support, his scientific guidance for this thesis.

I would also like to express my gratitude to the members of my jury, Prof. Pierre-François Leyvraz, Dr. Sandra Martelli, Dr. Philippe Büchler, and Dr. Catherine Dehollain who took time to read and exam may thesis.

Special thank to Dr. Brigitte M. Jollès-Haeberli (Hôpital Orthopédique de la Suisse Romande), my clinical co-advisor, for her kindly collaboration and preparing the clinical protocol. I deeply appreciate her helpful advices, support, enthusiasm, comments and sympathy. I would like to thank Dr. Alain Farron (HOSR) for his great knowledge in shoulder problem, for his support and helpful comment on this thesis. Also, I would like to thank Claude Pichonnaz, Jean-Philippe Bassin and Angelina Poloni for their important assistance in collecting the clinical data.

I wish to thank Jean Gramiger and Pascal Morel for the design of the wearable system and inertial sensors used in this project.

My gratitude goes to all my colleague, ex-colleague and friends of the LMAM: Danielle Alvarez, Anisoara Paraschiv-Ionescu, Valérie Besson, Ralucka Ganea, Julien Favre, Amine Merdassi, Hooman Dejnabadi, Bijan Najafi, Hossein Rouhani, Benoit Le Callennec, Shimba Sachio, Albin Kujawa, Julien Chardonnens.

I would like to thank my friends who participate to the measurement: Antonello Nesci, Julien Perruisseau, Frédéric Bongard, Fabio and Silvano Maturo, Laurent Bigler.

I express my deepest gratitude to my parents, my family who always encouraged and supported me. Finally, my biggest and warmest thanks go to my girl friend, Diane Duperret, for her love, patience and support.

This thesis was supported by the Swiss National Foundation under Grants FNRS N°405340-104752/1.

Contents

Chapter 1 Introduction and outline of the thesis

1.1 Introduction

The human shoulder system involves four segments, the *clavicle*, the *scapula*, the *humerus* and the *thorax*[1]. Four joints may be distinguished (Figure. 1.1):

- The *sterno-clavicular* (SC) joint, which articulates the clavicle by its proximal end onto the sternum.
- The *acromio-clavicular* (AC) joint, which articulates the scapula by its acromion onto the distal end of the clavicle.
- The *scapulo-thoracic* (ST) joint, which allows the scapula to glide on the thorax.
- The *gleno-humeral* (GH) joint, which allows the humeral head to rotate in the glenoid fossa of the scapula.

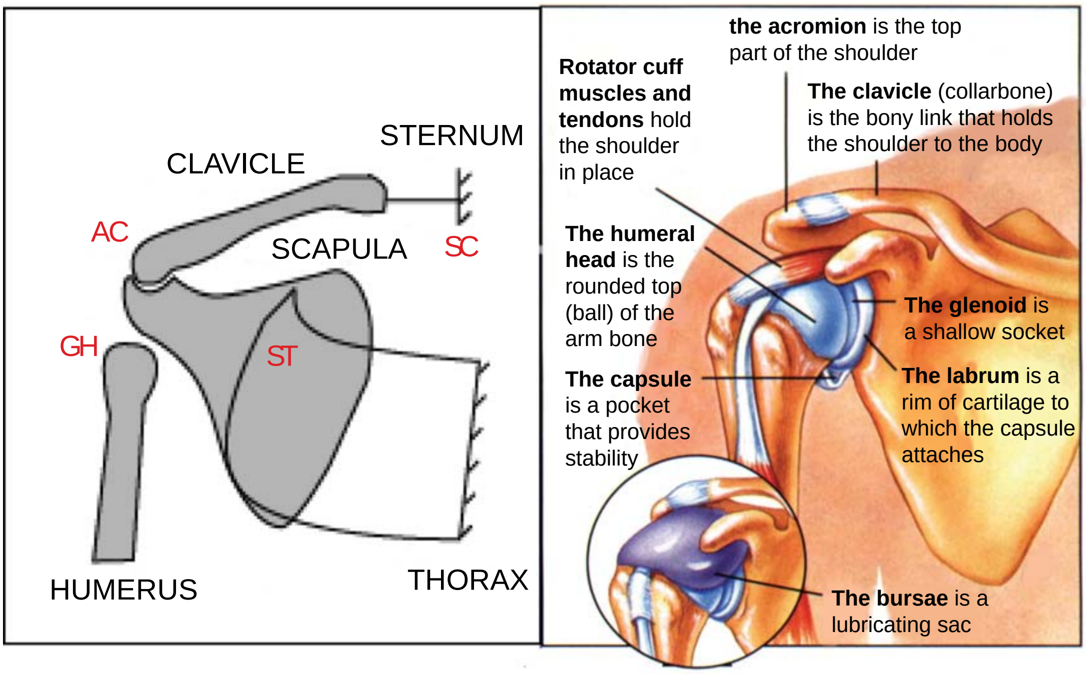

Figure 1.1: Shoulder segments and joints

The complex and interactive actions of these joints and segments give to the shoulder the highest range of motion among all the other joints of the human body. This very large mobility of the shoulder joint is mandatory to place the hand (and the arm) in every position of the surrounding space. Accordingly, in outcome measurements, the shoulder function may be summarised to the assessment of the humeral position relatively to the thorax and ground, whatever is the mobility in each intermediate joints and segments[2].

In contrast to the hip joint, which more closely approximates a true ball and socket joint, the shoulder joint can be compared to a golf ball and tee, in which the ball can easily slip off the flat tee. The stability to the shoulder joint, provided by the bones, is highly dependent on surrounding soft tissues such as capsule ligaments and the muscles surrounding the rotator cuff to hold the ball in place. Whereas the hip joint is inherently quite stable because of the encircling bony anatomy, it also is relatively immobile. The shoulder, on the other hand, is relatively unstable but highly mobile, allowing an individual to place the hand in numerous positions. It is in fact, one of the most mobile joints in the human body. The bones of the shoulder are held in place by muscles, tendons, and ligaments. Tendons are tough cords of tissue that attach the shoulder muscles to the bone and assist the muscles in moving the shoulder. Ligaments attach shoulder bones to each other, providing stability. For example, the front of the joint capsule is anchored by three glenohumeral ligaments. The rotator cuff is a structure composed of tendons that work along with associated muscles to hold the ball at the top of the humerus in the glenoid socket and provide mobility and strength to the shoulder joint. Two filmy sack-like structures called bursae permit smooth gliding between bones, muscles, and tendons. They cushion and protect the rotator cuff from the bony arch of the acromion.

The movements of the shoulder are: flexion-extension, abduction-adduction, internal-external rotation. The movements of flexion-extension are made in the sagital plane around the transverse axis.

The movements of abduction-adduction are made in the frontal plane around the antero-posterior axis. The rotation of the arm on its longitudinal axis can be carried out in any position of the shoulder[3] (Figure 1.2).

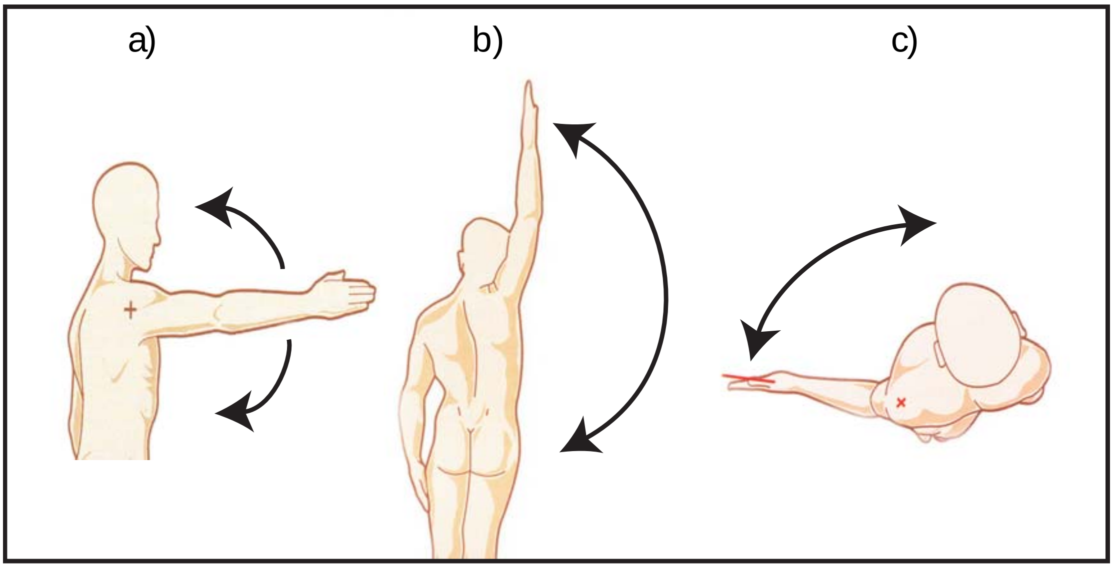

Figure 1.2: The movements of the shoulder are: a) flexion-extension, b) abduction-adduction, c) internal-external rotation.

1.2 Origins and causes of shoulder problems

The shoulder is easily injured because the ball of the upper arm is larger than the shoulder socket that holds it. To remain stable, the shoulder must be anchored by its muscles, tendons and ligaments[4]. Although the shoulder is easily injured during sporting activities [5,6,7] and manual labor[8,9], the primary source of shoulder problems appears to be the natural age-related degeneration of the surrounding soft tissues such as those found in the rotator cuff. The incidence of rotator cuff problems rises dramatically as a function of age and is generally seen among individuals who are more than 60 years old[10,11]. Overuse of the shoulder can lead to more rapid age-related deterioration.

Shoulder pain may be localized or may be felt in areas around the shoulder or down the arm. Disease within the body also may generate pain that travels along the nerves to the shoulder.

1.3 Shoulder pathologies

The symptoms of shoulder problems, as well as their diagnosis and treatment, vary widely, depending on the specific problem. The following is important information to know about some of the most common shoulder problems.

Dislocation

The shoulder joint is the most frequently dislocated major joint of the body. In a typical case of a dislocated shoulder, either a strong force pulls the shoulder outward (abduction) or extreme rotation of the joint pops the ball of the humerus out of the shoulder socket. Dislocation commonly occurs when there is a backward pull on the arm that either catches the muscles unprepared to resist or overwhelms the muscles. When a shoulder dislocates frequently, the condition is referred to as shoulder instability. A partial dislocation in which the upper arm bone is partially in and partially out of the socket is called a subluxation[4].

Signs and symptoms: The shoulder can dislocate either forward, backward or downward. When the shoulder dislocates, the arm appears out of position. Other symptoms include pain, which may be worsened by muscle spasms, swelling, numbness, weakness and bruising. Problems seen with a dislocated shoulder are tearing of the ligaments or tendons reinforcing the joint capsule and, less commonly, bone and/or nerve damage. Preoperatively, patient's shoulder range of motions were 90° flexion, 30° extension, 80° abduction, 5° external rotation and internal rotation[12].

Separation

A shoulder separation occurs where the collarbone (clavicle) meets the shoulder blade (scapula). When ligaments that hold the joint together are partially or completely torn, the outer end of the clavicle may slip out of place, preventing it from properly meeting the scapula. Most often, the injury is caused by a blow to the shoulder or by falling on an outstretched hand[8].

Signs and symptoms: Shoulder pain and, occasionally, a bump in the middle of the top of the shoulder (over the acromioclavicular (AC) joint) are signs that a separation may have occurred[13,14]. Lack of power or apprehension in abduction /external rotation may be observed[8].

Torn Rotator Cuff

Rotator cuff tendons often become inflamed from overuse, aging or a fall on an outstretched hand or another traumatic cause. Sports or occupations requiring repetitive overhead motions or heavy lifting can also place a significant strain on rotator cuff muscles and tendons[15]. Over time, as a function of aging, tendons become weaker and degenerate. Eventually, this degeneration can lead to complete tears of both muscles and tendons. These tears are surprisingly common. In fact, a tear of the rotator cuff is not necessarily an abnormal situation in older individuals if there is no significant pain or disability[15]. Fortunately, these tears do not lead to any pain or disability in most people. However, some individuals can develop very significant pain as a result of these tears and they may require treatment[16,17,18].

Signs and Symptoms: Typically, a person with a rotator cuff injury feels pain over the deltoid muscle at the top and outer side of the shoulder, especially when the arm is raised or extended out from the side of the body[8]. Motions like those involved in getting dressed can be painful. The shoulder may feel weak, especially when trying to lift the arm into a horizontal position. A person may also feel or hear a click when the shoulder is moved. Pain or weakness on internal or external rotation of the arm may indicate a tear in a rotator cuff tendon[8]. The patient also feels pain when lowering the arm to the side after the shoulder is moved backward and the arm is raised[15]. The patient has loss of power. For the large rotator cuff tears, there is a paralysis[15].

Frozen Shoulder (Adhesive Capsulitis)

As the name implies, movement of flexion abduction and internal/external rotation of the shoulder is severely restricted in people with a “frozen shoulder”[19]. This condition, which doctors call adhesive capsulitis, is frequently caused by an injury that leads to a lack of use due to pain. Rheumatic disease progression and recent shoulder surgery can also cause frozen shoulder. Intermittent periods of use may cause inflammation[8]. Adhesions (abnormal bands of tissue) grow between the joint surfaces. There is also a lack of synovial fluid, which normally lubricates the gap between the arm bone and socket to help the shoulder joint move. It is this restricted space between the capsule and ball of the humerus that distinguishes adhesive capsulitis from a less complicated painful and stiff shoulder. People with diabetes, lung disease, rheumatoid arthritis, and heart disease, or those who have been in an accident, are at a higher risk for frozen shoulder. A frozen shoulder is more common among women than men. People between the ages of 40 and 70 are most likely to experience it[8,20].

Signs and symptoms: With a frozen shoulder, the joint becomes so tight and stiff that it is nearly impossible to carry out simple movements, such as raising the arm. Stiffness and discomfort may worsen at night[8,21]. The non dominant shoulder is slightly more likely to be affected[20].

Fracture

A fracture involves a partial or total crack through a bone. The break in a bone usually occurs as a result of an impact injury, such as a fall onto the shoulder. A fracture usually involves the clavicle or the neck (area below the ball) of the humerus[4,22,23].

Signs and symptoms: A shoulder fracture that occurs after a major injury is usually accompanied by severe pain.

Arthritis of the Shoulder

Arthritis is a degenerative disease caused by either wear and tear of the cartilage (osteoarthritis) or an inflammation (rheumatoid arthritis) of one or more joints. Arthritis not only affects joints, but may also affect supporting structures such as muscles, tendons and ligaments.

Signs and symptoms: The usual signs of arthritis of the shoulder are pain, particularly over the acromioclavicular joint, and a decrease in shoulder motion. Range of motion may be severely limited in patients with marked osteoarthritis, but commonly the restriction is moderate[8].

1.4 Outcome evaluation

Outcome research is a relatively new field of interest in orthopedics[24]. The rapidly rising cost of healthcare with its financial impact on the individual and national economy, and deficiencies in clinical research methods such as a patient-oriented evaluation, which are pain, functional and quality-of-life assessments, have stimulated the emergence of this concept.

A large variety of scores with different designs are used to report the results of shoulder treatment making it difficult to compare the patient's outcome[25] and there is a need for additional development of an evaluation system, a need for a "gold standard" outcome measurement.

The effectiveness of a shoulder arthroplasty, a rotator cuff repair or a glenohumeral stabilization in relieving pain and/or improving function has been well documented[4,8]. The influence of surgical procedures on quality-of-life must be positive. But health–related quality of life encompasses not only pain and physical functioning, but other related domains such as social functioning and vitality. In addition, shoulder surgeons require now more subtle comparisons between two potentially efficient treatments (e.g. two types of prosthesis, arthroscopic vs. open surgery). Therefore, the use of instruments that have increased sensitivity and specificity in evaluating quality-of-life compared to traditional scoring systems is needed to enhance the surgeon's ability to assess the overall outcome in patients after a shoulder treatment.

Different techniques exist to assume the functional handicap of the patients and we review them in the next subsection. Their use, however, has been hindered by the long time required to perform the measurements, the limited information they provide and by their prohibitive cost in time and money.

Despite the fact that the shoulder is necessary each time one wants to position the hand in the tridimensional space, this joint still remains one of the least explored functionally. This paradox is due to two facts. Moving the shoulder is very easily accessible to a detailed clinical analysis. As a result, the diagnosis has been developed on a clinical basis. The indications for surgery have mostly been laid down several years ago and rely on analysis and experience. However effective in practice, this approach allows neither for the quantification of the spatio-temporal parameters when moving the shoulder, nor for the assessment of the physical activity of everyday life in a reliable way.

Most quantitative approaches to shoulder movement analysis are dealing only with the measurements of the range of motion in a particular direction[26,27,28], without paying attention to all the combinations of movements of the shoulder that are mandatory to place the hand in the space. In fact, the importance of knowing the combination of the adjunct rotation and conjunct rotation may be crucial to estimate the functionality of the shoulder before and after surgery (Chapter 5). They are just instrumented clinical examinations that improve the precision and accuracy of the measurement itself but miss all practical and quality-of-life implications such as the mobility (Chapter 4), the working level (Chapter 6), and the number of movement of flexion, abduction and internal/external rotation (Chapter 5) for patients.

1.5 Objectives

We aim to measure the kinematics of the shoulder in real life conditions and during a long period involving a high number of kinematics patterns. Our method might be seen as less accurate than stationary systems such as camera-based devices for angle and position estimations. Yet, this new approach will be much more effective in clinical outcome evaluation as it will provide information on the working level, movement of flexion abduction and internal/external rotation, mobility that are useful and adapted to the patient and his/her shoulder movements in daily situations.

The accuracy of such an ambulatory system will increase with the number of sensors used. However, we are restricted by ambulatory environment conditions, where the use of a large number of sensors and attachment tools represent a serious constraint for the subject's movement. We will have to find the best balance between the complexity and the accuracy of the new measuring system. Laboratory comparisons with the current "gold standard" will be done to insure the reliability of the new ambulatory system in term of kinematic performances.

Finally, as far as biomechanical aspects are concerned, we are not intending to present any shoulder model providing features related to ligaments and muscles activity. These features are surely important but they are not concerned with this study of outcome evaluation. Our objective is to provide significant kinematic parameters needed for the outcome evaluation of the patient's shoulder during daily activity and to determine how these parameters change in a pathological case. These objectives will be reached by devising a configuration of sensors that allows the evaluation of the motor performance of the shoulder.

1.6 Outline of the thesis

The thesis is organized in eight chapters.

The first chapter, Introduction and outline of the thesis, introduces the shoulder pathologies and the objectives.

The second chapter describes the clinical shoulder's questionnaires and provides an overview of the existent methodologies (Clinical score questionnaires, stationary systems, ambulatory systems) to assess the shoulder pathologies and provide outcome evaluation.

In the chapter three, we propose a new ambulatory device based on inertial sensors for shoulder movement analysis. Then, objective scores derived from inertial sensors were described to evaluate objectively the shoulder function. 10 patients were studied before surgery and 3, 6 and 12 months after surgery. The results were compared to clinical questionnaires.

Outcome evaluation in shoulder treatment should consider the movement of the dominant arm during daily activity. The fourth chapter presents a new method based on one of the kinematic score described in the chapter 3 to estimate the upper-limb dominant segment. 31 healthy subjects carried our ambulatory system during their daily activity. The quantification of the upper-limb dominant segment during the gait, standing and sitting postures is described.

The characterization of the number of the flexion, abduction and internal/external rotation is required to show how the dominant and non dominant shoulders move. The fifth chapter provides a method using 3D angular velocities of the humerus to detect the number of movements of flexion, abduction and internal/external rotation of the humerus. The combination rate of conjunct and adjunct rotation and the speed of the arm movements and the number of movements per hour during the daily activity were studied.

The arm elevation allows a better evaluation of the shoulder performance. The arm elevation (known as the working level) is evaluated subjectively in clinical questionnaire. The sixth chapter presents an algorithm to estimate the actual working level of the shoulder during the daily activity. The working levels were separated into different levels to 0° to 160° per step of 20°. A new working level score, based on the duration and the frequency of the working levels reached, was developed.

The seventh chapter shows the effectiveness of the proposed methods in clinical applications. 26 patients were studied at baseline and 3, 6 and 12 months after shoulder surgery for the short-term measurement. 10 patients were studied before and 3, 6 months after shoulder surgery for the long-term measurement during daily activity.

The last chapter presents the conclusion of this thesis and the perspectives for the future studies.

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Chapter 2 Overview of the methodologies used to assess the shoulder function

2.1 Introduction

The importance of recognizing the result of a medical procedure has long been recognized in surgery and particularly in orthopedic surgery. Outcome assessment has been given new impetus during the past decade as the emphasis has shifted from the era of expansion and technical development to one of assessment and accountability. Variable definitions of outcome have been used previously to assess outcome after shoulder treatment. Some of these, such as the Constant score or the American Shoulder and Elbow Surgeons score are widely used, though none has been accepted as the universal standard.

The difficulty lies in attempting to quantify a treatment result, which from the patient's viewpoint is best expressed in subjective terms. A technical success from the surgeon's standpoint may not necessarily have had a significant impact on a patient's pain and quality of life and thus from his or her perspective is a failure.

This imbalance has recently been addressed with the reporting of a large number of outcome scoring scales like the Short Form 36 (SF-36), the European Quality-of-Life Group 5 dimensions score (EQ-5D), the Disabilities of the Arm, Shoulder and Hand score (DASH), the Constant score or the Simple Shoulder Test (SST). But the increasing number of outcome measures for assessing the results of shoulder pathology treatment illustrates the need for an objective method of assessing the results i.e. a gold standard outcome measure. The choice of the ideal outcome measure to assess a shoulder pathology remains a complex issue. For example, should one put more emphasis on the patient's overall improved well-being and pain status, or should more emphasis be placed on the technical success of the surgery? Movement analysis using sensors is a non invasive way to answer this dilemna.

The goal of this chapter is to show the existing instruments for the evaluation of the shoulder pathology and its functionality during daily activities. It will describe three different approaches : 1) the clinical scores, 2) the stationary systems and 3) the ambulatory measurement system.

2.2 Clinical scores

The clinical scores include the American Shoulder and Elbow Surgeons Evaluation Form (ASES), the Constant score, the Disabilities of the Arm, Shoulder and Hand score (DASH) and the Simple Shoulder Test (SST). We will discuss each of these scoring systems, commenting on their strengths and weaknesses.

2.2.1 ASES Shoulder Evaluation Form

The instrument consists of a physician assessment section[1] and a patient self-evaluation section. Evidence has been provided that the use of the self-evaluation section is independent from the clinical assessment[2]. The physician assessment section includes physical examination and documentation of range of motion, strength, and instability, and demonstration of specific physical signs. No score is derived for this section of the instrument. The patient self-evaluation section has 11 items that can be used to generate a score. These are divided into 2 areas: pain (1 item) and function (10 items). The response to the single pain question is marked on a 10-cm visual analog scale (VAS), which is divided into 1-cm increments and anchored with verbal descriptors at 0 and 10 cm. The 10 items in the function area of the ASES include activities of daily living such as putting on a coat, etc. There are more demanding activities such as lifting 10 pounds above shoulder height and throwing a ball overhead. Finally, there are 2 general items: doing daily work and doing regular sport. There are 4 response options, from 0 (unable to do) to 3 (not difficult). Because of this, the responsiveness of the individual items is rather poor, especially in very active patients. As an example, if a patient found an activity somewhat difficult prior to treatment, he or she would have no difficulty whatsoever after treatment to improve by 1 category. The final score is tabulated by multiplying the pain score (maximum 10) by 5 (therefore the total possible is 50) and the cumulative activity score (maximum 30) by 5/3 (therefore the total possible is 50) for a total of 100. Evaluation of the instrument has been undertaken in a population of patients with shoulder dysfunction, such as instability/dislocation or humeral fracture[2]. Test-retest reliability reached acceptable levels separately for the pain and the function dimensions, as well as for the total score (ICC=0.79, 0.82, 0.84, respectively)[2].

2.2.2 The Constant Score

The Constant score[3] has become the most widely used shoulder evaluation instrument in Europe. This scoring system combines physical examination tests with subjective evaluations by the patients (Table 2.1). The subjective assessment consists of 35 points and the remaining 65 points are assigned to the physical examination assessment. The subjective assessment includes a single item for pain (15 points) and 4 items for activities of daily living (work, 4 points; sport, 4 points; sleep, 2 points; and positioning the hand in space, 10 points). The objective assessment includes the range of motion (forward elevation, 10 points; lateral elevation, 10 points; internal rotation, 10 points; external rotation, 10 points) and power (score based on the weight that the patient can resist in abduction for a maximum of 25 points). The total possible score is therefore 100 points. The publication by Constant[3] in which he describes the instrument does not include methodology about how it was developed and, more specifically, the rationale for the selection and relative weighting of the items. It is indeed unknown why the specific weights were assigned to the items (pain 15%, function 20%, range of motion 40%, strength 15%). The strength of this instrument is that the method for administering the tool is quite clearly described, which is an improvement on pre-existing tools.

This Constant score combines 4 items of function with 5 items of physical examination. As these measure fundamentally different attributes, they should be measured separately as opposed to being combined for a total score.

This instrument is weighted heavily on range of motion (40%) and strength (25%). Although this may be useful for differentiating patients with significant rotator cuff disease or osteoarthritis, it is useless for patients with instability. In fact, all the patients with instability of the shoulder scored nearly perfectly (95-100 points) despite having problems of sufficient magnitude that requested surgical intervention[4].

The reliability of this measurement tool has been evaluated on a limited basis[4]. Several authors tried to determine the clinical value of the Constant score[4,5,6], which has gained an important role in the functional evaluation of the shoulder joint[3,7]. The Constant score shows a very high inter-observer reliability of 97% compared to other scoring techniques[7]. Conboy et al.[4] measured the reliability on 25 patients with varying diagnoses of shoulder syndromes. They demonstrated that the 95% confidence limit between observers was 27.7 points and within observers was 16 points.

2.2.3 Disabilities of the Arm, Shoulder and Hand (DASH)

The American Academy of Orthopaedics Surgeons (AAOS) along with the Institute for Work & Health (Toronto, Ontario, Canada) developed an outcome tool to be used for patients with any joint of the upper extremity. This instrument called the Disabilities of the Arm, Shoulder and Hand Measurement tool, or DASH, is made available by the AAOS (Table 2.1). A brief description of the methodology for the item generation and the initial item reduction phases has been published[8]. In 1999, the AAOS and Institute for Work & Health developed and published a User’s Manual for the DASH outcome measure[9]. The complete development and testing of the instrument is detailed in this manual. The DASH is a 30-item questionnaire designed to evaluate “upper extremity-related symptoms and measure functional status at the level of disability.” Disability is defined as “difficulty doing activities in any domain of life (the typical domains for one’s age/sex group) due to a health or physical problem”. Concepts covered by the DASH include symptoms (pain, weakness, stiffness, and tingling/numbness), physical function (daily activities, house/yard chores, shopping, errands, recreational activities, self-care, dressing, eating, sexual activities, sleep, and sport/performing art), social function (family care occupation, socializing with friends/family) and psychological function (self-image). The item generation was carried out by first reviewing the literature. Thirteen scales were combined to produce an initial pool of 821 items. Item reduction was carried out in 2 steps. Three members of the collaborative development group reviewed the original items.

Reliability, validity and responsiveness of the DASH have been evaluated in patients with disorders of all major areas of the extremity, i.e. shoulder, elbow, wrist and hand[10,11,12,13,14]. The test-retest reliability has been demonstrated in patients with shoulder pain and in those with elbow disorders (ICC = 0.92)[14], as well as both proximal and distal upper extremity disorder populations (ICC = 0.96)[11], which exceeds recommended standards for the test-retest reliability.

The major criticism of this tool is that the item generation phase did not include interviews with patients with the conditions of interest. It has been well documented that physicians are poor judges of patient's status and will be poor judges of what is important to patients.

A problem with the DASH is that it has been found to correlate strongly with pain levels, which could lead to elevated scores in a population with multitrauma[12]. Acutely injured patients were excluded from the original evaluation study for the DASH[11] and no study has specifically evaluated the use of the DASH in trauma populations. Nevertheless, the DASH is often used as a comparative standard in the design of joint-specific instruments for the upper extremity.

This instrument is intended for patients with any condition of any joint of the upper extremity. The patients can complete the questionnaire before a diagnosis is established.

Unfortunately, the broader scope of this instrument makes it less attractive to use in a clinical trial. Many of the items may seem irrelevant to patients with specific conditions. In addition, this instrument has been shown to be less responsive than other shoulder condition specific instruments making it less efficient as a research tool.[15,16,17]

2.2.4 The Simple Shoulder Test (SST)

The SST consists of 12 questions with “yes or no” response options. The instrument combines subjective items and items that actually require the patient to perform a physical function (Table 2.1). For example, the patient is asked “Does your shoulder allow you to sleep comfortably?” which is subjective and “Can you lift 8 pounds to the level of your shoulder without bending your elbow?” which requires the patient to perform the maneuver.

The item generation and reduction was based on Neer’s evaluation[18], the ASES evaluation[19], and observation of patients’ complaints by the instrument developers. This instrument is able to distinguish between patients with different diagnoses (osteoarthritis, rheumatoid arthritis, avascular necrosis, subacromial impingement, rotator cuff tears, frozen shoulder, traumatic anterior instability, and multidirectional instability) and a normal shoulder function. Some data on the SST following patients after rotator cuff repair indicates that the instrument can be used to determine what functional improvement the average patient obtains post treatment. The SST is unlikely to be sensitive to small but clinically important changes in patient function because of the dichotomous response options (yes or no). For the same reason, the instrument is likely have poor function to differentiate patients with varying severity of the same condition.

That the 12-item SST with “yes” and “no” responses was somewhat more responsive than the 30-item DASH questionnaire was an unexpected finding. The validity of the SST has been supported in a variety of shoulder conditions, but previous authors have tended to focus on differentiating properties[20,21,22,23,24,25]. The SST is simple to administer and score, and carries a relatively low response burden, giving it an advantage in the clinical situation.

Table 2.1 Reviewed patient self-evaluation instruments for assessment of upper extremity trauma.[26]

Instrument (time for patient to complete)	Dimensions	Number of items	Advantages and disadvantages
ASES (3min) Total	• Pain • Instability • Activities of daily living	6 1 10 17	• Not extensively used in trauma population. • Most often used in the assessment of rotator cuff or shoulder instability.
Constant Score (10min) Total	• Pain • Activities of daily living • Range of motion • Power	1 4 4 1 10	• The method for administering the tool is quite clearly described which is an improvement on pre-existing tools. • It is not useful for patients with instability.
DASH (6min) Total	• Daily activities • Symptoms • Social function • Work function • Sleep • Confidence	21 5 1 1 1 1 30	• Most validated measure of extremity functional status. • Easy to use. • Use of the DASH has been found to strongly correlate with pain levels which may be problematic in a population with multi-trauma.
SST (3min) Total	• Physical function	12 12	• The instrument is able to distinguish between patients with abnormal and normal shoulder function. • The SST is unlikely to be sensitive to small but clinically important changes in patient function because of the dichotomous response options (yes or no).

2.3 Stationary systems

The main categories of stationary systems are:

1. Optoelectronic systems.
2. Electromagnetic systems.
3. Ultrasound systems.
4. Electromyogram (EMG) systems.

We will describe each system in the following parts.

2.3.1 Optoelectronic systems

The optoelectronic systems, such as Optotrak, Codamotion (Figure 2.1) or Vicon (Figure 2.2), are used for real-time 3D motion tracking and analysis. They give the 3D positions. They contain a sensor unit and small infrared light emitting diodes (LED's) markers. The LED's markers are placed on the subject to be analyzed. They are non-invasive system. There are two kinds of markers: active (e.g Codamotion) and passive (e.g Vicon).

Figure 2.1 : Codamotion system
a) sensors unit; b) small infrared light emitting diodes markers.

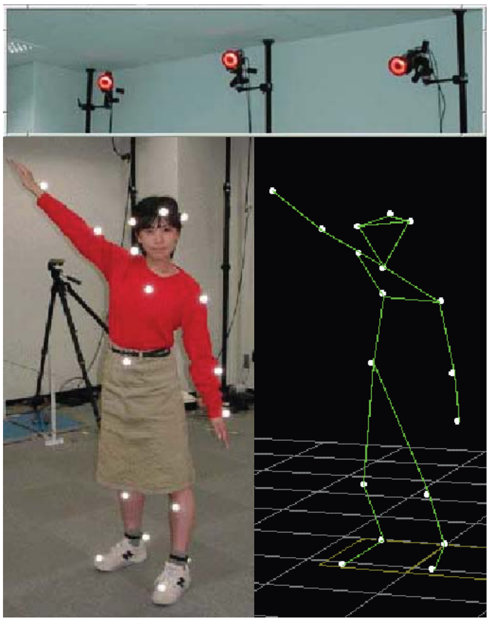

Figure 2.2: Vicon system.

Several authors used optoelectronic systems for their studies. Triolo et al.[27] used the Optotrack system for modeling the postural disturbances caused by the upper extremity movements. They described the design, validation and application of a dynamic 3D model of the upper-extremity in order to estimate postural disturbances generated by movements of the arms. Hébert et al.[28] used the same device for measuring 3D scapular attitudes. They developed a method to obtain 3D scapular movements and assess their concurrent validity and reliability. Roux et al.[29] used a six-camera optoelectronic system and markers on the head, trunk, arm, forearm, hand and shoulder girdle (Figure 2.3) to evaluate the kinematics of the shoulder and the upper limb.

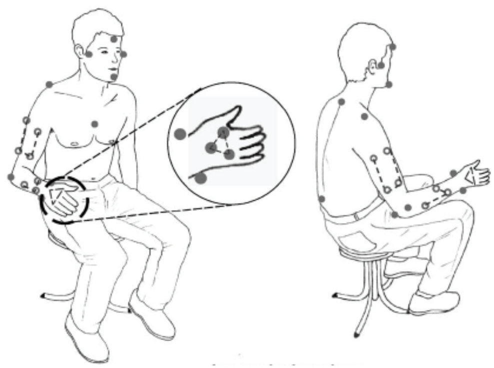

Figure 2.3: Led's markers for the study of Roux et al.[29]

Yang et al.[30] evaluate with the Vicon system the motion quality of upper limb target-reaching movements. They attached 3 markers on the humerus, 3 markers on the forearm and 3 markers on the hand (Figure 2.4). They found general indices for the quality measure of plane target-to-target movement.

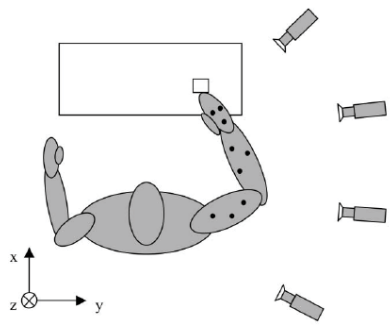

Figure 2.4: Top view of the set-up for the experiments Yang et al.[30]

Hingtgen et al.[31] used the Vicon system to develop a 3D upper extremity kinematic model to obtain joint angles of the trunk, shoulder and elbow. They attached markers on the trunk, the shoulders, on the elbows and on the wrists (Figure 2.5). Their model can accurately quantify upper extremity arm motion in laboratory, which may aid in the assessment and planning of stroke rehabilitation.

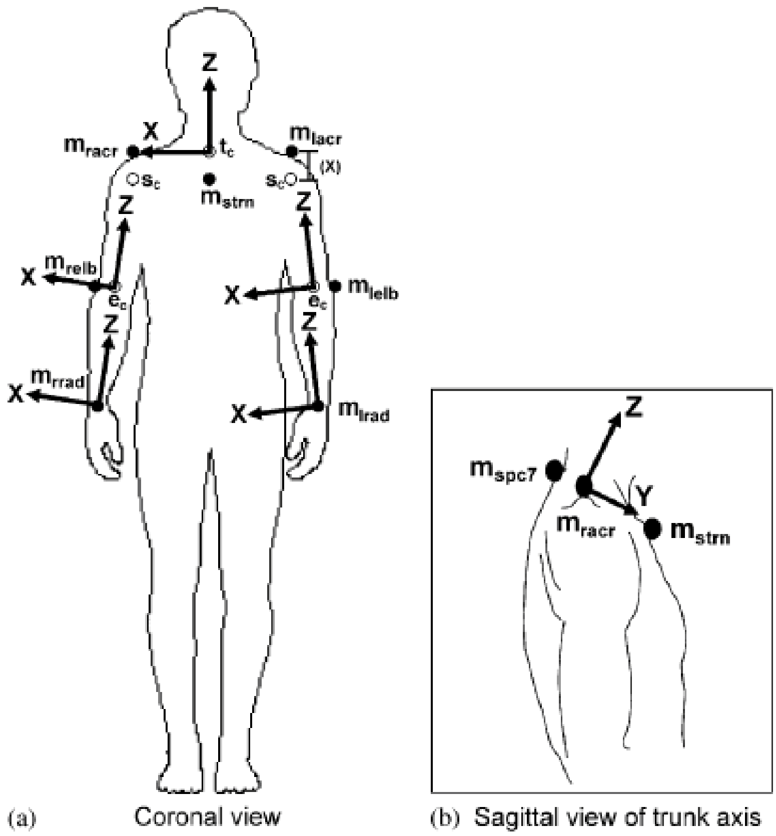

Figure 2.5: Local coordinate axes systems for the upper extremity model, (a) coronal view, (b) sagittal view of trunk axis. Markers are shown as black circles.

Other studies used the Vicon system to evaluate the upper extremity motion during wheelchair propulsion[32,33] to analyze the gait[34,35,36,37,38] or to validate a new measuring system[39].

2.3.2 Electromagnetic systems

The electromagnetic systems such as Fastrak, Minuteman or Liberty (Figure 2.6) are for real-time 3D motion tracking and analysis. They give the 3D orientation (Euler, quaternion) and the segment position.

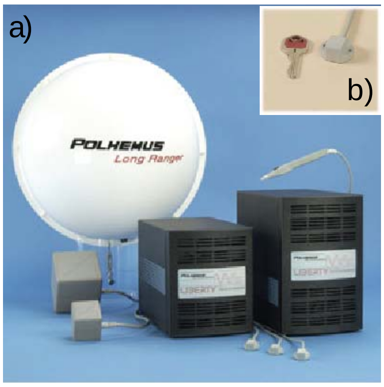

Figure 2.6: Liberty system a) system unit and source; b) electromagnetic sensors.

The Fastrak or Liberty system is adapted for laboratory measurement. The Minuteman system is the portable version of the Liberty system and allows long term measurements outside a laboratory, for example with a pocket PC-like computer. The system electronics unit contains the hardware and software necessary to generate and sense the magnetic fields, compute position and orientation, and interface with the host computer via RS-232 or USB. The source contains electromagnetic coils enclosed in a molded plastic shell that emit magnetic fields. The source is the system's reference frame for sensor measurements (Figure 2.6 a)). The sensor contains electromagnetic coils enclosed in a molded plastic shell that detect the magnetic fields emitted by the source. It is a lightweight small cube, and the sensor's position and orientation is precisely measured as it is moved. The sensor is a completely passive device, having no active voltage applied to it (Figure 2.6 b)). The update rate is 240 Hz per sensor. Besides their precision (< 1deg), these systems suffers from magnetic material in the environment.

Meskers et al. [40] used an electromagnetic system to record and process a methodology to obtain complete 3D kinematics of the shoulder including joint rotations. Several authors[41,42,43] developed a system to validate the assumption that the center of the rotation in the glenohumeral joint can be described based on the geometry of the joint.

They compared two methods of the glenohumeral rotation center detection. They concluded that the method to estimate the glenohumeral center of rotation as the center of a sphere through the glenoïd surface, with the radius of the humeral head, appears to be valid. Other authors used electromagnetic systems to evaluate the direct 3D measurement of the scapula[44,45] and to describe the 3D movement of the shoulder[46,47,48,49]. McClure et al.[45] proposed a study to describe 3D scapular motion patterns during dynamic shoulder movement. Direct measurement of active scapular motion was accomplished by insertion of two 1.6-mm bone pins into the spine of the scapula (Figure 2.7). They found that during active scapular plane elevation, the scapula upwardly rotated (mean [SD] = 50° [4.8°]), tilted posteriorly around a medial-lateral axis (30° [13.0°]) and externally rotated around a vertical axis (24° [12.8°]). Lowering the arm resulted in a reversal of these motions in a slightly different pattern. The mean ratio of glenohumeral to scapulothoracic motion was 1.7:1.

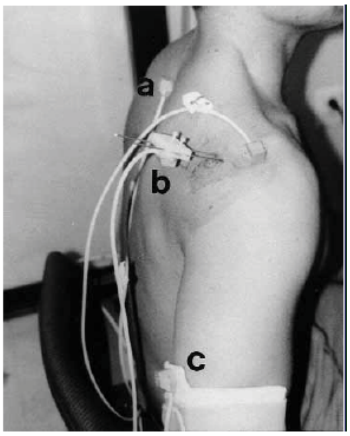

Figure 2.7: Subject with magnetic sensors attached: thoracic sensor (a), scapular sensor attached to bone pins (via plastic guide) inserted into the scapula (b) and humeral sensor mounted on custom cuff applied to the distal humerus (c). The sensor mounted on the acromion (not labeled) was used for data related to another study.

Fayad et al.[44] attached Liberty sensors, one on the chest, one on the acromion and one on the humerus (Figure 2.8). They obtained a full 3-D kinematic description of the scapula achieving a reliable, complex 3-D motion during humeral elevation and lowering. Their results were almost the same as the work of McClure et al. but with the non invasive way.

Figure 2.8: Magnetic sensor position of Fayad et al.[44] study.

Finley et al.[50] used the same sensors configuration as Fayad et al. to evaluate the effect of the sitting posture on 3D scapular kinematics. Other authors used an electromagnetic measuring system to evaluate the shoulder movements during wheelchair propulsion[51] and for gait analysis[52,53,54].

2.3.3 Ultrasound systems

The ultrasound-based motion analysis systems such as the Zebris system are used to measure the spatial coordinates of markers. The measurement head with three transmitters, emitting ultrasound signals at specific intervals, which are recorded by the active markers (the measurement frequency being 100 Hz), is located in front of the person (Figure 2.9). With the knowledge of the ultrasound speed, the distance between each marker and the measurement head, i.e. the location of transmitters, can be calculated from the time delay of the transmission. With the knowledge of the distance between the active markers and each of the three transmitters of the measurement head and the spatial coordinates of the transmitters, the spatial coordinates of the markers can be calculated using the method of triangulation any time during the measurement.

Figure 2.9: Zebris Ultrasound system.

Illyés et al.[55,56] described a method to analyze shoulder joint movements using the Zebris ultrasound system. They attached triplet of markers on the clavicle, scapula, upper arm, lower arm and thorax (15 markers in total) (Figure 2.10).

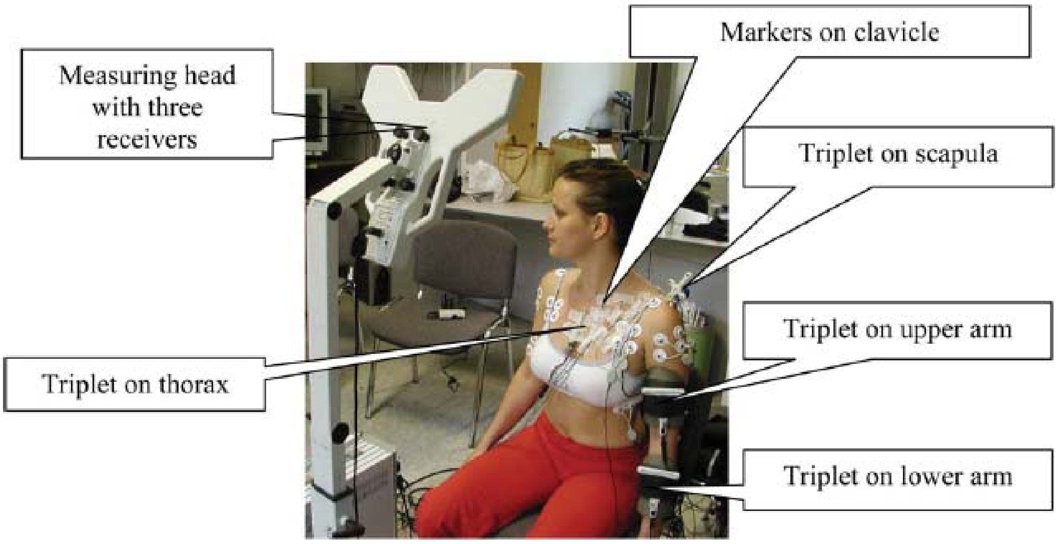

Figure 2.10: Measurement arrangement for the study of Illyés et al.[55]

They characterized the motion of the humerus and the scapula relative to each other by their rotation as well as the relative displacement between the rotation centers of the scapula and the humerus. But the main problem of this study was that the 15 markers were connected to the main unit, making it cumbersome.

We have also used a Zebris ultrasonic motion capture capture system as a reference to compare gyroscopes data during gait[57]. We compared data from a gyroscope attached on the shank to the angular velocity calculated from the data of the Zebris markers (Figure 2.11).

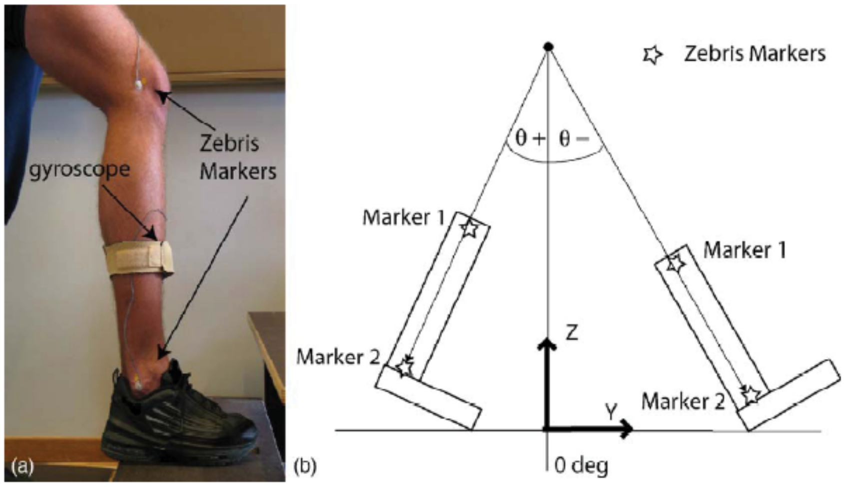

Figure 2.11: (a) Positions of the gyroscope and Zebris markers. (b) Angle θ definition: 0° is defined when the subject is motionless and calibrated with the system Zebris positions marker 1: (y1, z1); positions marker 2: (y2, z2).

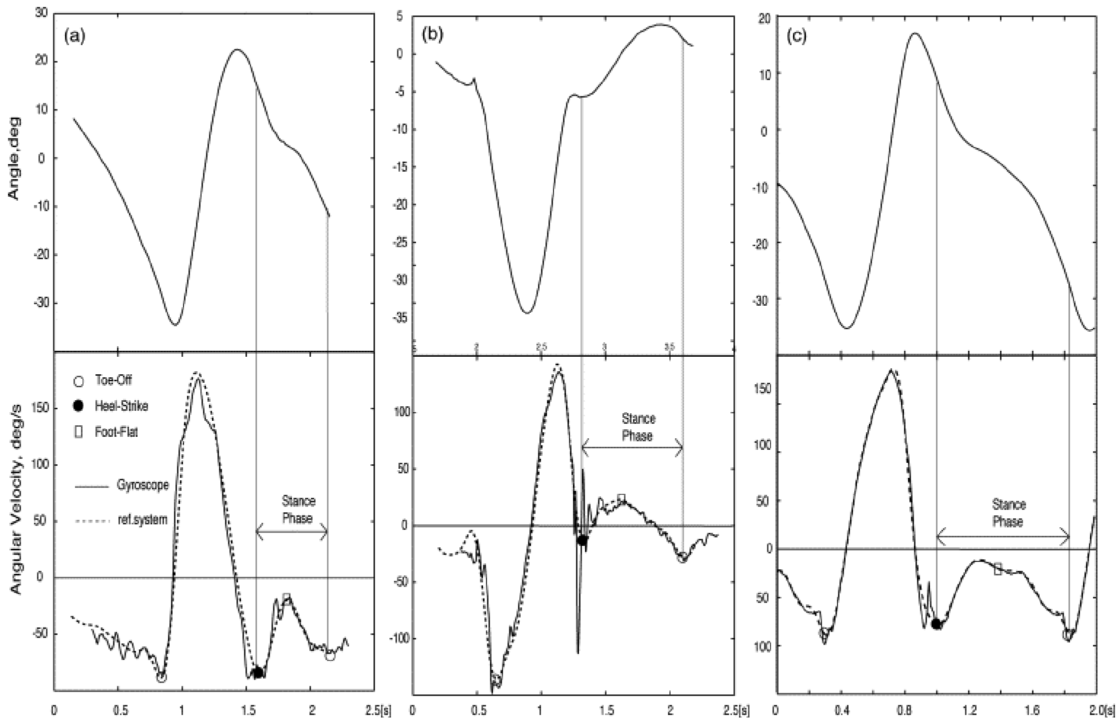

Figure 2.12: Shank antero-posterior rotation and its angular velocity for (a) cycle stair descent. (b) Cycle stair ascent. (c) Cycle walking on the flat. Each case signal measured with gyroscope is compared with angular velocity estimated from ultrasonic reference system (Zebris). A positive peak of angular velocity is observed during stance phase for stair ascent only.

We showed that the gyroscope measured sufficiently accurately the shank rotation and particularly the magnitude of the angular velocity at foot-flat compared to the reference motion system (Figure 2.12). It can be observed that, during stance, the shank angle increased for stairs ascent (leading to a positive angular velocity) while, during stairs descent and walking the shank angle decreased (negative angular velocity). The difference between stairs ascent, stairs descent and walking was always visible at the time of foot-flat.

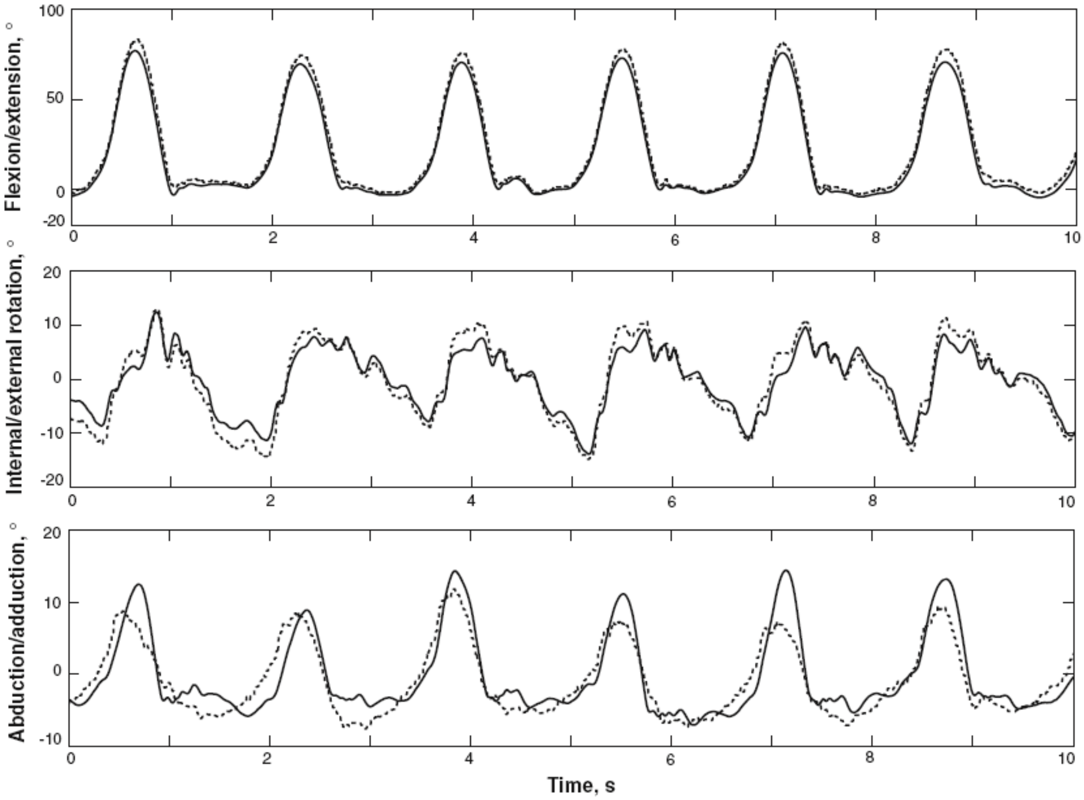

Figure 2.13: 3D angles for ten typical seconds of treadmill walking of a healthy subject. The continuous line corresponds to the reference system angles, and the dotted line to the system proposed by Favre et al.[58]

Favre et al.[58] compared the 3D knee angles measured by the Zebris system to the 3D knee angles measured by the 3D gyroscope of the thigh and the shank. The precisions obtained were, respectively 2.5°, 2.1°, and 2.7° for the flexion-extension, the internal-external rotation and the abduction adduction (Figure 2.13).

2.3.4 EMG systems

Electromyography (EMG) is a recording technique using skin or needle electrodes for evaluating muscular activities. EMG is performed using an electromyograph that detects the electrical potential generated by muscle cells when they are excited.

The amplitude of the electromyogram signal is estimated of 0.1 to 5 mV, and its bandwidth of 0-10kHz. The EMG systems are used in laboratory (Bagnoli desktop

EMG system, Motion Lab EMG system, DataLINK EMG system, MyoSystem, Zebris EMG system) or ambulatory (MyoMonitor, RSI protector, InnoSense, DataLOG EMG system, TeleMyo, MyoGuard) to estimate the activity of the different muscles (Figure 2.14). Needle and skin electrodes used for EMG are illustrated in Figure 2.15. Surface EMG electrodes (instead of fine-wire electrodes) are now used in order to avoid pain or restriction of movements, and the reliability of these electromyographic data has been established[59].

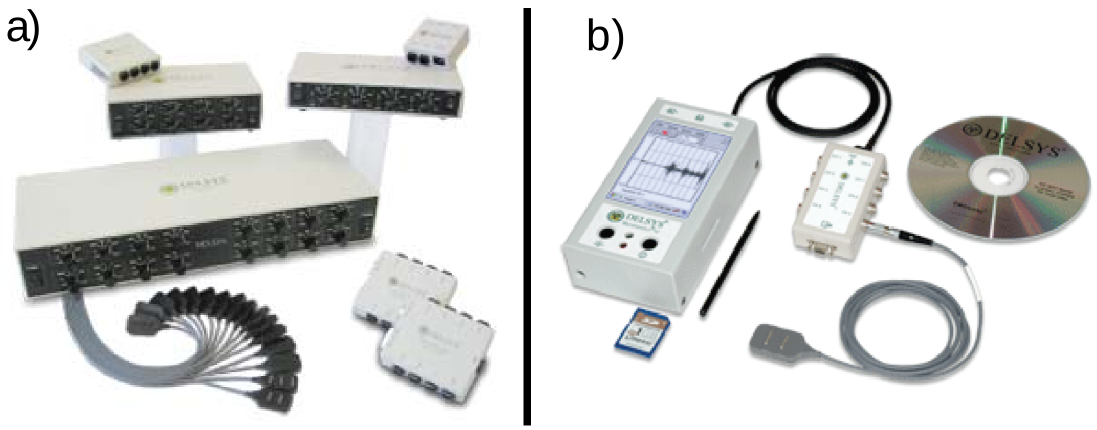

Figure 2.14: EMG systems, a) Bagnoli desktop EMG system, b) Myomonitor ambulatory EMG system (Delsys).

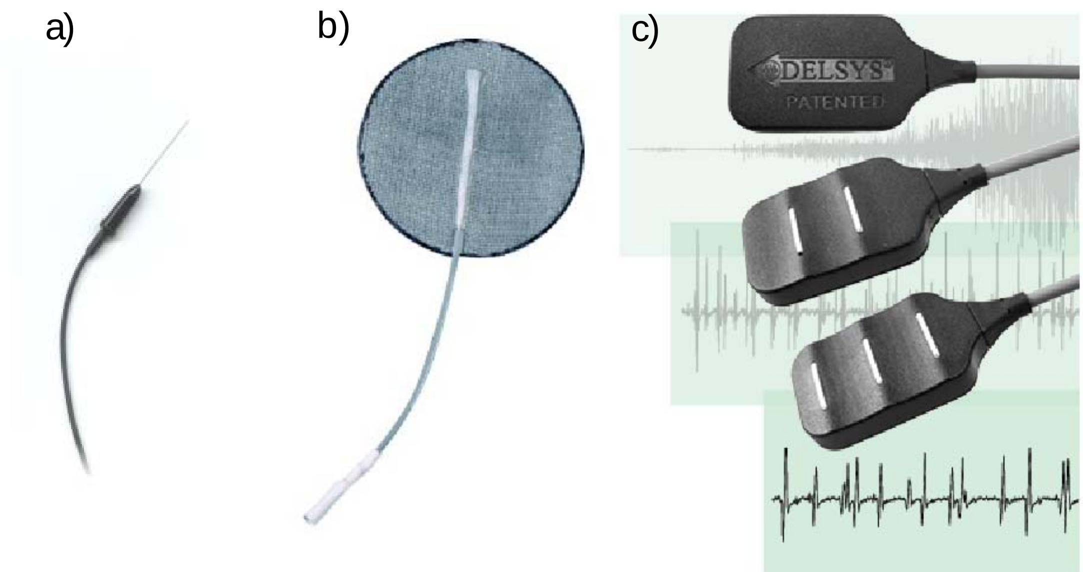

Figure 2.15: Electrodes for EMG systems, a) needle electrode, b) surface electrode (patch), c) surface electrode (parallel-bar EMG electrode, single and double differential models).

Electromyographic studies have been used to analyze the role of shoulder muscles activities, in rotator cuff tears[60,61], shoulder instability[62], impingement syndrome[63], rehabilitation programs[64], with various kinds of elementary arm movements analysis (such as flexion, abduction, internal/external rotation) or complex movements analysis[65] since the pioneering work of Inman[66]. Kelly et al.[60] evaluated the differential firing patterns of the rotator cuff, deltoid and scapular stabilizer muscle groups in normal control subject and in patients with symptomatic and asymptomatic 2-tendon rotator cuff tears. They used the Motion Lab system to collect the electromyographic activity of 12 muscles. They found that the asymptomatic patients had significantly greater ($p<0.05$) subscapularis activity than symptomatic patients during the internal rotations task. Illyés et al.[61] compared the muscle activity of patients with multidirectional shoulder instability with the control group during pull, forward punch, elevation and overhead throw. Signals were recorded by surface EMG (Zebris EMG system) from eight different muscles (Figure 2.16). The results gave rise to the assumption that the centralization of the glenohumeral joint and the reduction of instability are attempted to be ensured by the organism through increasing the role of rotator cuff muscles and decreasing the role of the deltoid, biceps brachii and pectoralis maior muscles.

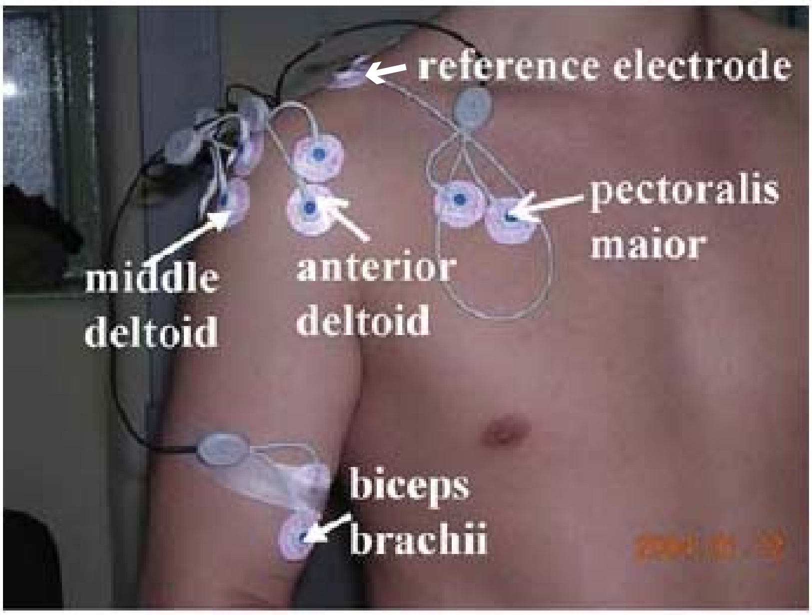

Figure 2.16: Location of surface EMG electrodes, Illyés et al.[61]

Lin et al.[59] used an electromagnetic measuring system and surface electromyography systems to analyze 3D shoulder complex movements during functional tasks and compare motion patterns between subjects with and without a shoulder dysfunction. They found a significant alteration in shoulder complex kinematics and associated muscular activities for the group with shoulder dysfunction relative to the group without shoulder dysfunction. EMG signal is affected by the bone position, muscle length and muscle contraction velocity[67]. Therefore, maximal voluntary electrical activity or maximal voluntary contraction is usually recorded and normalized in order to be able to compare patients at different times. Relations between EMG and force directions or muscle strength[68] have been studied and used to compare patients before and after shoulder surgery[69] or when they perform difficult tasks over their heads, such as construction workers[70]. David et al.[68] used combined EMG and isokinetic strength analysis in healthy subjects to identify activation patterns of several muscles acting on the shoulder joint during isokinetic internal and external rotation. They found a strong association between electrical activity and moment production of the mouvement in the subscapularis and infraspinatus ($R^2 = 0.95$ and 0.72, respectively) at the low and high angular velocities. Sporrong et al.[70] used the MyoGuard ambulatory EMG system to map the muscular engagement and postures of construction workers undertaking ceiling fitting and to compare these results to those from the laboratory studies. The EMG data showed that nearly 50% of the work was spent with trapezius activity that exceeded that of the reference contraction used and that the time spent in muscular relaxation was 10%.

In the current literature, shoulder EMG is used in order to appreciate the muscles activities of a known upper limb action or pathology.

2.3.5 Conclusion

Since 1990, few authors have been tested the hypothesis that movement analysis was susceptible of providing objective and quantifying evidences of treatment evaluation. But all these measurement tools are accessible nowhere else than in a few research institutes. They are often complex, allowing only range of motion or power analysis. In the current practice, these techniques are not applicable for routine evaluation of patient outcomes. The physicians lack a convenient and simple method to reliably assess the activity and the daily shoulder performance of their patients before and after shoulder treatment.

Furthermore, standard motion capture systems can be very expensive and the use of markers tends to make them cumbersome. As a result, fielding these techniques typically requires a dedicated laboratory whose cost is often prohibitive, which has hindered the use of such measuring systems. Although these systems provide complete kinematics, they are complex, necessitate specially trained personnel and require a relatively long time for the measurement implementation and the data analysis. The most important disadvantage of these systems is that the subject must stay inside a closed and restrained volume.

2.4 Sensors for ambulatory technologies

The ambulatory systems compared with the stationary systems are usable in laboratory, but also outside the laboratory, they are compact and lightweight. These ambulatory systems are composed of a central unit: “datalogger”, and one or more inertial sensors. Sensors used in ambulatory sytems are mainly : either composed of electrogoniometer, accelerometer, gyroscope, or magnetometer. In the following, some of the main features of the accelerometer, gyroscopes and magnetometer and ambulatory systems are presented.

2.4.1 Electrogoniometer

A goniometer is an electrical potentiometer that can be attached to a limb to measure a joint angle (Figure 2.17).

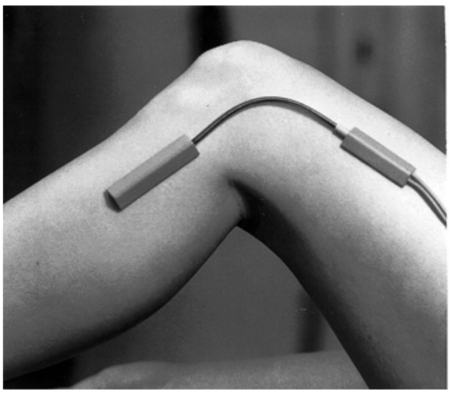

Figure 2.17: Electrogoniometer attached to the knee.

Currently, electrogoniometers, either potentiometer-based or flexible ones, have been applied to measure the range of motion for the wrist and the forearm[71,72,73,74] or the knee[75] and shoulder strength[76]. Goniometer have practical limitations. Main issues are sensor attachment and the need for a range of devices to fit different-sized limbs. They are vulnerable to breakage where they cross a joint. Other common issues are difficulties in alignment with the joint, the determination of joint centres of rotation, the restriction of movement by the device or incomplete decoupling of the measurement of motion in the two planes (cross-talk)[71]. The size, weight and physical location of the goniometer can be critical.

2.4.2 Accelerometers

Miniature accelerometers are often used to analyze human movement[77,78,79]. Recently, several methods based on accelerometry were developed to measure the arm movement[80], to track the upper limb motion[81,82] and to monitor the daily activity[83].

The recent progress in Micro Electro Mechanical Systems (MEMS) has provided new miniature and low power accelerometers which are promising as wearable and ambulatory technology.

The accelerometer is normally placed on the part of the body whose movement is being studied. For example, accelerometers are attached to the thigh or shank to study the leg movement during walking[84] or to the wrist to measure Parkinsonian bradykinesia and tremor in Parkinson disease[85].

Accelerometers are often used to measure body segment inclination (relative angle to vertical). Using several accelerometers provide the relative inclination of one segment to another and an estimation of the body posture needed for physical activity monitoring[83]. Combined with other inertial sensors, accelerometers can also provide 3D body segment orientation[80].

Triaxial accelerometers with signal conditioning circuits are now integrated on a single chip. These sensors can be battery powered and are well adapted tools for long-term ambulatory measurements. An example of tri-axial accelerometers including conditionning module is presented in Figure 2.18.

2.4.3 Gyroscopes

Rotations are always present in human movements. Angular rate sensors or gyroscopes can measure these rotations. A gyroscope consists of a vibrating element coupled to a sensing element, acting as a Coriolis sensor. The Coriolis effect is an apparent force that arises in a rotating reference frame and is proportional to the angular rate of rotation.

Several studies used gyroscopes to analyze the gait[57,58], monitor the daily activity[83]and track upper limb motion[81,82].

Typically, the orientations of a body segment can be determined by integrating the angular velocity measured by the gyroscopes. However, small offset error in the gyroscope signal will introduce large integration errors (drift). The principles for measuring orientation of a moving body segment fusing gyroscopes and accelerometers have been described by Favre et al.[54].

An example of tri-axial gyroscsopes including conditionning module is presented in Figure 2.18.

Figure 2.18: Tri-axial accelerometer and tri-axial gyroscope including conditioning module.

2.4.4 Magnetometer

The magnetometer is an instrument for measuring the direction and/or intensity of magnetic fields (Figure 2.19).

Figure 2.19: 3D magnetometer from Intersense.

Sensitive to the earth's magnetic field, a magnetometer gives information about north magnetic and therefore an absolute reference in the horizontal plan. It can be used to correct the drift of rotation around the vertical axis, when using a gyroscope. Zhou et al.[81,82] used 3D magnetic sensors, 3D gyroscopes and 3D accelerometers to track the three degrees of orientations of upper limb segments. Although, the system was not used in a ambulatory setup, they demonstrated the practicality of these sensors fusion for orientation tracking in real-time. However, ferromagnetic materials around the magnetometer will disturb the local magnetic field and will therefore distort the orientation measurement. This interference impedes applications such as ambulatory motion monitoring where magnetic field distorsion is presented in the environment.

2.4.5 Ambulatory systems

Xsens system

The Xbus Master from Xsens (Figure 2.20) is a lightweight (330g) and portable device that controls several Motion Trackers (MTx). The Xbus Master samples digital data from the MTx‘s and supplies power to the MTx’s. Each motion tracker is composed of 9 sensors: 3D accelerometers, 3D gyroscopes and 3D magnetometers.

Figure 2.20: Xbus Master of Xsens.

The Xbus Master can be connected to a PDA or PC via a serial cable or a wireless connection. The MTx's provides 3D orientation as well as kinematic data: 3D accelerometer, 3D gyroscope and 3D magnetometer. Several studies used the Xsens system to estimate upper-imb orientation [81,82,86]or gait[87]. Luinge et al.[86] described a method to measure the orientation of the lower arm with respect to the upper arm with the Xsens system. They found that the accuracy of the method was limited by the accuracy of the sensor to segment calibration.

Delsys system

The Myomonitor system from Delsys (Figure 2.14 b)) is an EMG system for ambulatory applications. This device can be linked to EMG sensors, a 3D accelerometer, a 3D gyroscope, EKG sensors, respiratory sensors, a goniometer and footswitch. Two systems are available: a wireless system that sends data over a wireless local area network (WLAN) or an autonomous datalogger. They control up to 16 channels.

SULAM system

The Strathclyde Upper-limb Activity Monitor (SULAM)[88,89,90] consisted of a pressure transducer, adapted to function as an electro hydraulic activity sensor, which used atmospheric pressure as a reference. The activity sensor consisted of a small pressure sensor attached to a length of fine fluid-filled tubing open at the free end (Figure 2.21).

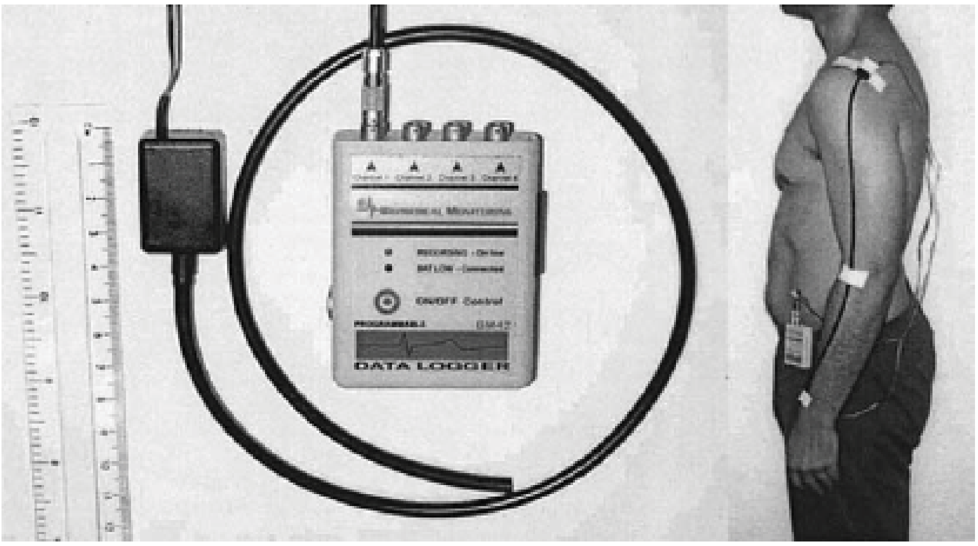

Figure 2.21: The Strathclyde Upper-Limb Activity Monitor (SULAM) and datalogger (left) and the SULAM being worn by participant (right). The SULAM was attached to the outer aspect of both upper limbs along the following reference points: acromion process, lateral epicondyle and lateral border of the radius.

By attaching the transducer to the shoulder and the free end of the tube to the wrist, the output signal was related to the vertical displacement of the wrist relative to the shoulder. Because the activity sensor measured the vertical displacement, it was not affected by precise anatomic location or orientation unlike accelerometers. This device needs a calibration, so that when the free end of the tube was at the same level of the sensor, the output signal was adjusted to zero.

KinetiSense system

KinetiSense is a small lightweight wireless device that integrates motion detection and electromyography (Figure 2.22).

Figure 2.22: KinetiSense sytem (CleveMed).

3D accelerometers and 3D gyroscopes provide 3D motion while two channels of EMG record muscle activity. The KinetiSense hardware is comprised of two small lightweight units connected by a thin flexible cable, the Command Module and the Motion Sensor. The system includes the Bluetooth radio for wireless real-time data transmission, a memory card long term monitoring and a re-chargeable battery. The Command Module can be clipped to a belt or band and the Motion Sensor positioned on the body where the motion monitoring is desired.

MiniSun IDEEA system

MiniSun system is an ambulatory system for energy expenditure and physical activity monitoring (Figure 2.23).

Figure 2.23: MiniSun system.

The system has been used for physical activity assessment, gait analysis, energy expenditure estimation, and functional capacity evaluation[91,92,93]. Each set of sensors includes orthogonal accelerometer to measure inclination of body segments and movement (acceleration) in 2 orthogonal directions.

DynaPort MiniMod system

The DynaPort MiniMod is a modular wireless system consisting of small ambulatory monitors and a remote control unit for synchronization and event logging (Figure 2.24).

Figure 2.24: MiniMod system (DynaPort) with two inertial modules.

The MiniMod consists of three orthogonally mounted accelerometers and a local memory card for data storage. The unit is powered by two AAA 1.5 V batteries. Data is collected at 100 Hz and stored on the SD card. It is designed for monitoring human posture, balance, energy consumption and gait parameters[94,95].

Physilog system

The Physilog is a portable data logger for long-term recording designed by the EPFL-LMAM (Figure 2.25). The device weigths 215 grams (batteries included) and can record up to 16 channels with 16 bits resolution (0−3V). The sampling rate configuration for each channel is programmable between (0.001−1500Hz). The data is stored on a removable SD memory card. The Physiolog datalogger can operate continuously up to 24 hours on rechargeable batteries.

The Physilog system has been used for human movement analysis in daily conditions or in labs to characterize the changes in moving ability in terms of type of pathology: osteoarthritis, balance, pain and movement disorder.

Figure 2.25: Physilog system.

Several clinical fields involving the locomotion system and especially orthopedics[58,96,97,98], elderly people study[99,100,101,102], neurology[85], gait analysis[57,103,104,105,106] and quality of life[83,107,108] are concerned. The ambulatory system designed in this study was based on the Physilog system and it is described in Chapter 3.

Other systems

Bussman et al. used an accelerometry-based upper-limb activity monitor to study the physical activity. The activity monitor is based on long-term (>24 h) ambulatory monitoring of signals from body-fixed accelerometers and consists of four accelerometers, a portable data recorder and a computer with analysis programs[109,110,111,112].

The Table 2.2 shows the comparison between different ambulatory systems.

2.5 Conclusion

We described three different ways of outcome evaluation in shoulder treatment. First, the clinical questionnaires such as DASH, SST and Constant are the most common tools used to evaluate the functionality of the shoulder. Although the time to complete the questionnaires is short for the patient, they give subjective scores. Second, the stationary systems based on camera, magnetic field and ultrasound system are accurate for the 3D orientation of body segments, but they are unable to give an evaluation during outdoor measurements and during daily activity. Finally, the ambulatory system which is the best solution for outdoor and long-term measurements but they have not been used for the shoulder function evaluation.

In this thesis, by using ambulatory monitoring and the adequate configuration of inertial sensors, we will provide new tools for the evaluation of the shoulder function. The type of movement and its intensity and the working level of the arm will be studied in the framework of protocols including short-term measurements at hospital and long-term measurements during daily activity.

Table 2.2 Comparison of the ambulatory systems.

Ambulatory system	Weight [gr]	Dimension (LxWxH), [mm]	Number of channel	Sensors	Sample rate [Hz]	Autonomy	Application	Additional remarks
Physilog	215	95x60x22	16	3D accelerometer 3D gyroscope ECG Footswitch Goniometer	0.001-1500	24h	Gait Risk of falling Physical activity Parkinson 3D joint movement Energy expenditure Sport	Bluetooth connection Two systems can be synchronized
Xsens	330	100x150x40	10	3D accelerometer 3D gyroscope 3D magnetometer	150	5h	3D joint movement	Bluetooth connection
Myomonitor (Delsys)	900	170x91x62	16	3D accelerometer 3D gyroscope ECG EKG Footswitch Goniometer Respiratory sensor	1024	8h	Gait Sport Muscle activity 3D joint movement Energy expenditure	Wireless transfer data available
SULAM	NA	NA	4	Pressure sensors	128-2048	8h	Upper limb activity	
KinetiSense	NA	NA	8	3D accelerometer 3D gyroscope EMG	128-2048	12h	Gait Muscle activity	Bluetooth connection
MiniSun IDEEA	59	70x54x17	8	2D accelerometer	256	60h	Gait Energy expenditure Physivcal activity	
MiniMod	55	64x62x13	3	3D accelerometer 1D/2D gyroscopes	100	60h	Gait Energy expenditure	Two systems can be synchronized

2.6 References

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Chapter 3 New devices and kinematic scores for the shoulder function assessment

***Abstract* -** A new method of scoring for the functional assessment of the shoulder and a new device to record shoulder movements of patients for long periods during a day are presented. 3D accelerometers and gyroscopes attached on both humerus, both spines of scapula (acromion) and on the thorax were used to differentiate a healthy from a painful shoulder. The method was first tested on 10 healthy volunteer subjects without any shoulder pathologies. Then, the system was tested on 10 patients with unilateral shoulder pathology (rotator cuff disease, osteoarthritis) before and after surgery (3, 6 months). To evaluate the system, 9 tests based on the Simple Shoulder Test (SST) were performed on each shoulder for each patient. Three scores were defined: the P score was based on the angular velocities and the accelerations of the humerus; the RAV score was based only on the angular velocities of the humerus; the M score was based on the sum of all moments of the humerus. Our kinematic scores indicated significant differences between baseline and follow-up ($p<0.05$) and differentiated patients with varying severities of the same condition. Our results showed a reliable technique of evaluating the shoulder pathology and surgery.

3.1 Introduction

We have described, in chapter 2, different assessment methods for judging the functional outcomes of shoulder procedures[1]. Some of these (such as the Disabilities of the Arm and Shoulder score (DASH)[2] and the Simple Shoulder Test score (SST)[3]) are widely used, though none has been accepted as the universal standard. Albeit validated, these instruments give only subjective scores and therefore give an incomplete answer on patient's shoulder evaluation.

Objective assessments like radiographs[4,5] provide a static estimation of the range of movement of the shoulder girdle but do not measure its dynamic functionality. This chapter proposes a different approach: measuring 3D kinematics from body-fixed sensors using an ambulatory recording device.

In this chapter, we had two aims: finding objective parameters (scores) for the assessment of the shoulder function based on body-fixed inertial sensors and evaluating the effectiveness of these parameters to quantify the difference of kinematics between a healthy and a painful shoulder. By validating such approach, we provide to the clinician a system to assess the shoulder's function and to find objective scores of their patients.

3.2 Methods

3.2.1 Materials

3.2.1.1 Sensors and signals

To record and analyze the movement of the shoulder girdle, five sites on the upper-limb were selected (Figure 3.1 a)): two sites on the anterior posterior part of the humerus, two sites on the superior part of the scapula's spine (acromion) and one site on the trunk. The site on the trunk was used to record physical activity based on the method of Najafi and al.[6] (see Chapter 4, 4.2.2 Body posture detection). The site on the humerus allowed the measurement of the movement of flexion, abduction and internal/external rotation, as it will be shown in this thesis. Fayad et al.[7] validated the attachment of the acromion-fixed sensors. They demonstrated that the average motion pattern of surface method was similar to that measured by the invasive technique[8]. Each site is composed by 3 MEMS gyroscopes and 3 MEMS accelerometers. All sensors in this study were miniature, solid-state devices (Figure 3.1 b)).

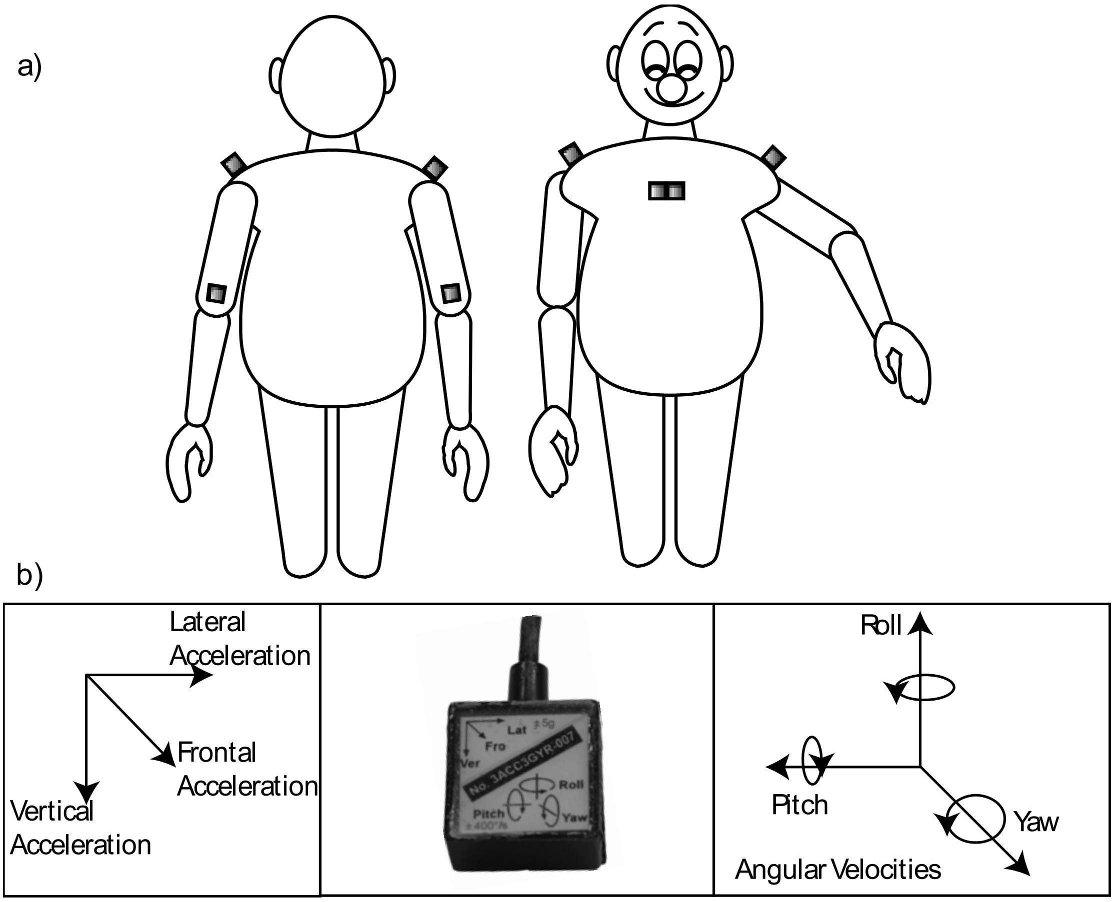

Figure 3.1: a) Position of the inertial sensors module including a 3D gyroscope and a 3D accelerometer. b) The sensitive axes of the 3D gyroscopes and 3D accelerometers.

The measured and selected range for each of the inertial sensors in the mentioned sites was evaluated in a laboratory condition and was presented in Table 3.2.

Table 3.2: The measured and selected range of each inertial sensor on the body.

Sensor site	Sensor type	Signal range	Selected range
Humerus	3D gyroscopes	±305°/s	±400°/s
Humerus	3D accelerometers	±3.2g	±5g
Acromion	3D gyroscopes	±280°/s	±400°/s
Acromion	3D accelerometers	±2.7g	±5g
Trunk	3D gyroscopes	±271°/s	±400°/s
Trunk	3D accelerometers	±2.2g	±5g

Movements of the humerus, the scapula and the thorax were recorded by 3D gyroscope units (*Analog device, ADXRS 250, ± 400 °/s)* and 3D accelerometer units (*Analog device, ADXL 210, ± 5g)*. Each module included three uni-axial gyroscopes assembled in the three perpendicular axes of pitch, roll, and yaw inside and three uni-axial accelerometers measuring the frontal, lateral and vertical accelerations.

3.2.1.2 Signals recording

All signals were recorded using the Physilog (Figure 2.25) portable data-logging system. It converted the analog signals to digital with an 16 bits A/D. Each Physilog data-logger could record 16 channels. As the number of the individual sensors was high (15 gyroscopes and 15 accelerometers), two synchronized Physilog systems were used. To store the data, the Physilog systems were equipped with a 512 Mbytes memory card (MMC or SD card). We used a sampling rate of 200 Hz to increase the temporal resolution. The signal from the sensors were amplified and low-pass filtered (cutoff frequency: 17 Hz) to remove any electronic noise[9,10]. The sensors and their conditioning electronics were packaged in a very small box (25x25x13 mm). With this regard, our proposed system appears especially promising: the sensors have low power consumption (112 mA) and the standard battery allows to record up to 8h. All of the data-analysis tasks were performed in MATLAB. In this thesis, we used only the sensors on both humerus and on the trunk. Different future applications of the scapula sensors are described in the chapter 8 (8.2 Future researches).

3.2.1.3 System architecture

The concept of the two synchronized Physilog systems (Physilog 1: Master; Physilog 2: Slave) were based on the integration of all the elements needed for shoulders ambulatory recording. Each Physilog system was a complete data-logger integrated with up to 16 inertial sensors with enough internal memory and battery to continuously record shoulder movements up to 8 hours.

Figure 3.2 shows a block diagram of both Physilog systems' architecture. Each system contains:

- A dedicated rechargeable NiMH battery.
- A flash memory with a capacity of 512 Mbytes (MMC or SD card).
- A one channel, 16 bits A/D converter with a 200Hz sampling rate.
- A precision, quartz based internal clock
- A Start/Stop button.

- 15 inertial sensors: 9 gyroscopes, 6 accelerometers, (Physilog 1); 6 gyroscopes, 9 accelerometers, (Physilog 2).
- Analog amplifiers and interface circuits.
- Anti-aliasing filters (a RC filter with a cut-off frequency of 17 Hz) to limit band-width of the analog signals.
- An 8 bits micro-controller.
- An 15x1 channels multiplexer (MUX).
- A LED to show the state of the system. Blinking in green when the system is recording. Blinking in red in case of errors. Red when being charged and green when the battery is fully charged.
- A synchronization cable. An 8 bits serial code is sent from the Physilog 1 (Master) to the Physilog 2 (Slave) to define the start, the stop and the acquisition periods.

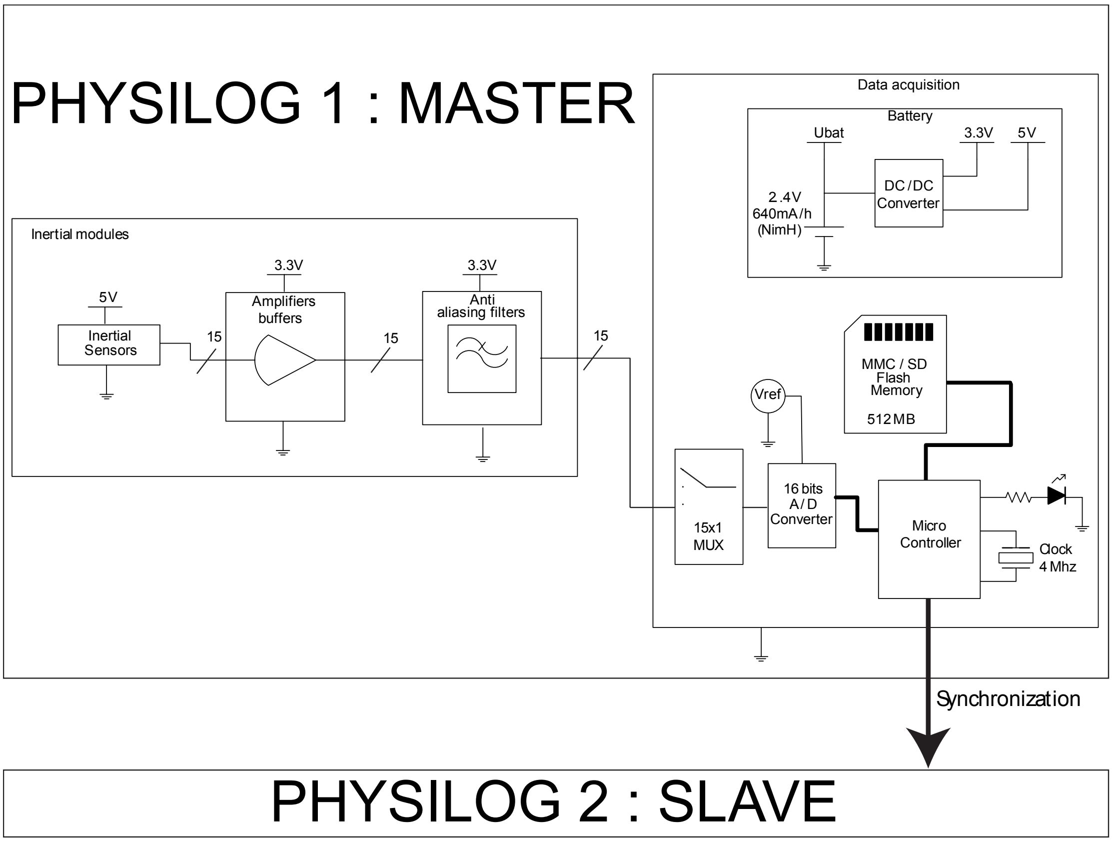

Figure 3.2: The internal architecture of the Physilog systems.

3.2.2 Subjects

10 healthy subjects (25.1 years old ± 4.1) and 10 patients with unilateral pathological shoulder (7 rotator cuff disease (7 rotator cuff repair) / 3 osteoarthritis (3 prosthetic shoulder arthroplasty): 4 women, 6 men: 62.4 years old ± 10.4) were studied. Nine tests representing some movements of daily activity based on the Simple Shoulder Test were carried out for both shoulders (Table 3.1) before surgery, 3 and 6 months after surgery. These tests were also carried out twice with one year interval on the same healthy subjects. Each test lasted 20 seconds and was video filmed for further validation of the movements and estimation of the false movements.

Table 3.1: Summary of the 9 tests carried out for painful and healthy shoulders. The subject was in standing position.

Tests	Description
1	Rest position
2	Hand to the back
3	Hand behind the head
4	Object ahead
5	Carrying 4kg in abduction
6	Carrying 8kg along the body
7	Hand to the opposite shoulder
8	Change a bulb
9	Object on the side (Elbow in 90°, ext/int.rotation

As described earlier, one module was fixed by a patch on the humerus (Figure 3.3). This way, the sensors measured the anterior elevation-extension, abduction-adduction and internal-external rotation of the shoulder.

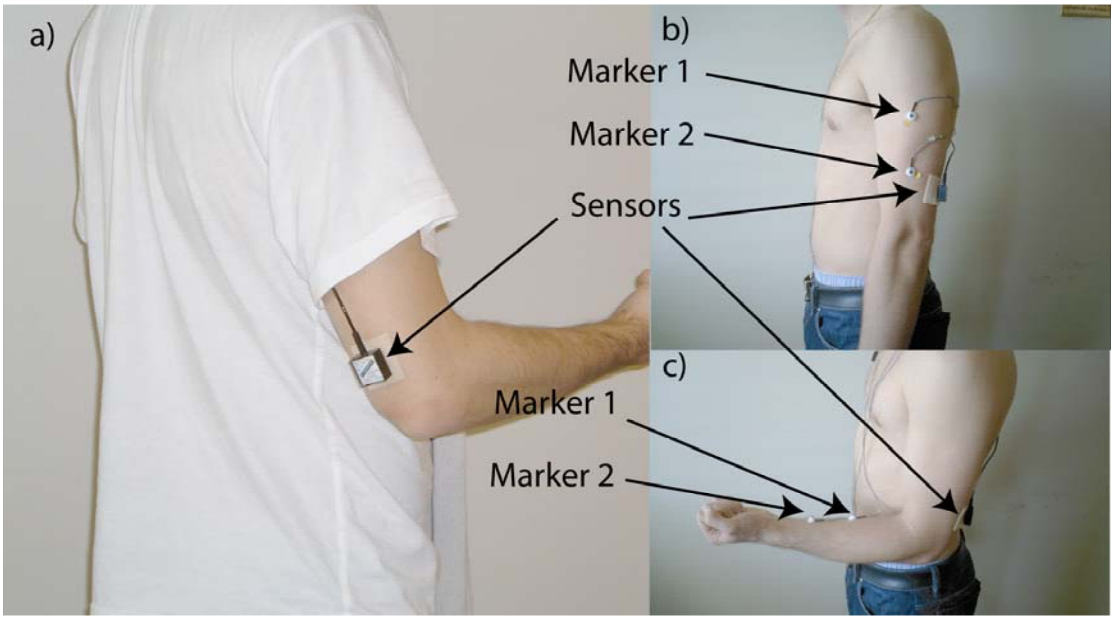

Figure 3.3: a) Position of the inertial sensors module including 3D gyroscope and 3D accelerometer. b) Position of the reference markers for abduction/adduction (yaw), flexion/elevation (pitch) rotation. c) Position of the reference markers for internal and external rotation (roll). The reference markers from the reference system were used for assessing our kinematic system.

The Simple Shoulder Test and the Disabilities of the Arm and Shoulder Score were filled out by each subject to estimate the validity of our method.

3.2.3 Angles estimation

Internal and external rotational movements (roll), extension and anterior elevation movements (pitch) and abduction and adduction movements (yaw) were estimated from 3D accelerometers and 3D gyroscopes. The accelerometers measure the gravity component, and using this feature, it is possible to measure the segment orientation when it is motionless[11]. Drift and DC components of the angular velocities were removed using wavelet transformation and considering the initial and final orientation of the segment based on the acceleration signals. The 3D angles were obtained after integration of the three angular velocities. Figure 3.4 shows the flow chart of the 3D angles estimation.

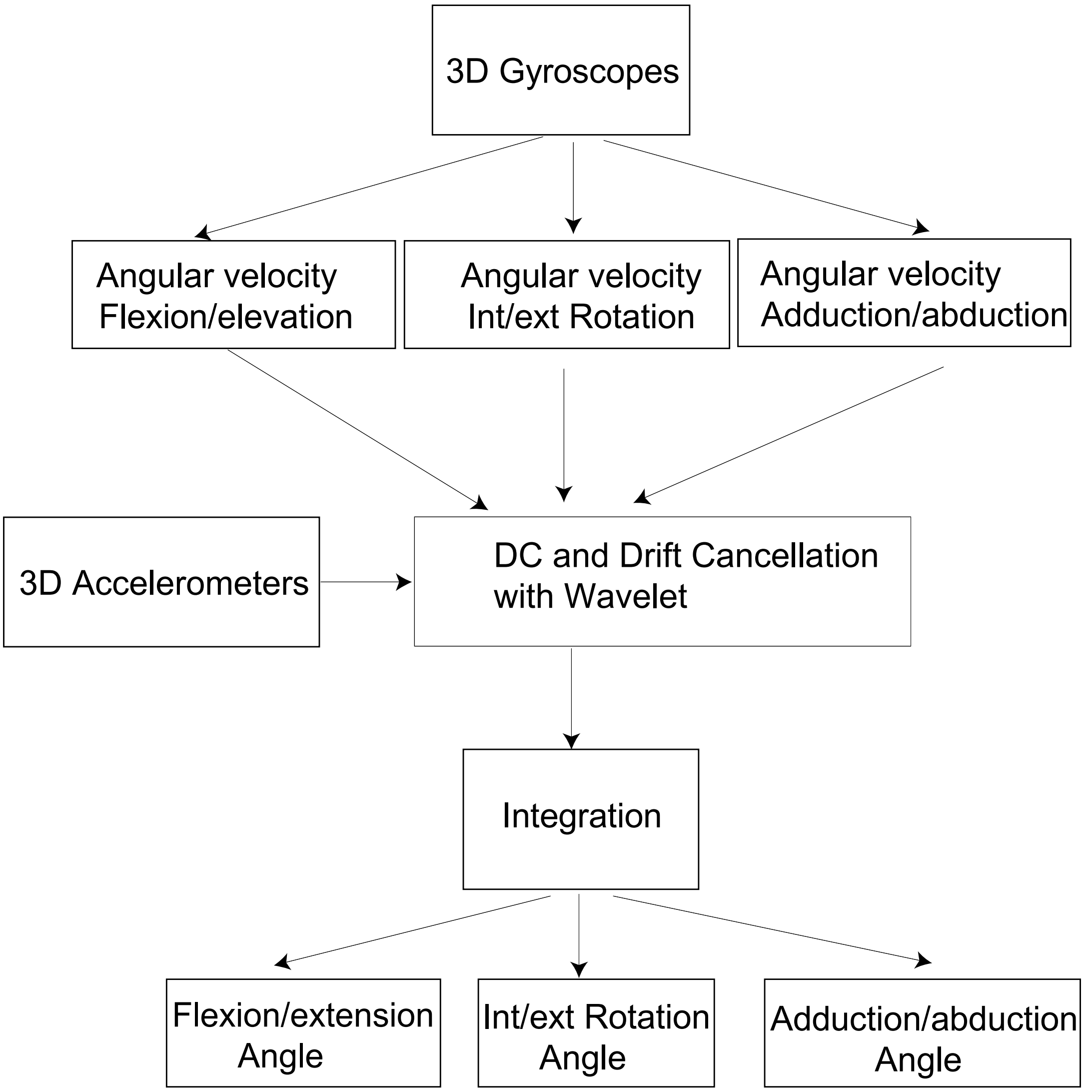

Figure 3.4: Flow chart for the angles estimation. Angles were estimated from the integral of angular velocity and by considering initial and final orientation of the accelerometers.

As a reference system, a Zebris CMS-HS ultrasound-based motion measurement system was used[12]. In this study, two ultrasound receivers were attached over the same segment (humerus) (marker 1, marker 2). Spatial marker positions (x, y, z) were recorded and used for calculation of orientation angles of the humerus. Synchronization between the reference and the Physilog systems was performed by electrical trigger. The angle data obtained by the body-fixed sensors were down sampled to 100Hz for comparison purpose. The flexion/extension and abduction/adduction angles of the humerus were estimated using the spatial coordinates of the microphone markers on the humerus (Figure 3.3 b)). The internal/external rotation angles of the humerus were estimated using the spatial coordinates of the microphone markers on the radius (Figure 3.3 c)). Basic movements like anterior flexion-extension, abduction, adduction and internal/external rotation were performed with our system and the reference system on 10 healthy subjects to assess the accuracy of our angles estimation method.

3.2.4 RAV score algorithm

Our second method consisted of providing a score by estimating the difference of kinematics between the healthy and the painful shoulder. It was based only on the angular velocities of the humerus. The 3D range of angular velocity (RAV) was calculated by the difference between the maximum and the minimum of angular velocity (deg/s) measured by 3D gyroscopes during each test in internal and external rotational (roll), flexion/extension (pitch) and abduction/adduction (yaw) directions for each subject. The RAVr parameter was estimated as the average of the sum of the RAV in the three axis of rotation.

$$RAVr = \frac{\left(\sum_{roll,pitch,yaw} range(angular\_velocity)\right)}{3} \qquad \text{(Equ. 3.1)}$$

The difference between a healthy and a painful shoulder (*Δ*RAVr) was expressed as the percentage of RAV of the healthy shoulder (*Δ*RAVr).

$$\Delta RAVr = (RAV_{healthy} - RAV_{painful}) / RAV_{healthy} \qquad \text{(Equ. 3.2)}$$

The RAV score is defined as the average of the ΔRAVr over all 9 tests.

$$RAV\ score = 1 - mean\left[\sum_{Test=1}^{9} \Delta RAVr\right] * 100[\%] \qquad \text{(Equ. 3.3)}$$

3.2.5 P score algorithm

The main idea was to observe the relationship between the accelerations and the angular velocities of the humerus. Figure 3.5 shows the difference between the healthy and the painful side for one axis and a patient. In order to estimate the difference between both sides, we calculated for each test the surface inside the curve for both sides. The simplest estimation of this surface was to calculate the area of the rectangle, which circumscribes the curve corresponding to the product of the acceleration range by the angular velocity range (Figure 3.5).

$$\mathrm{Pr} = \sum_{roll,pitch,yaw} range(acceleration) \cdot range(angular \quad velocity) \qquad \text{(Equ.3.4)}$$

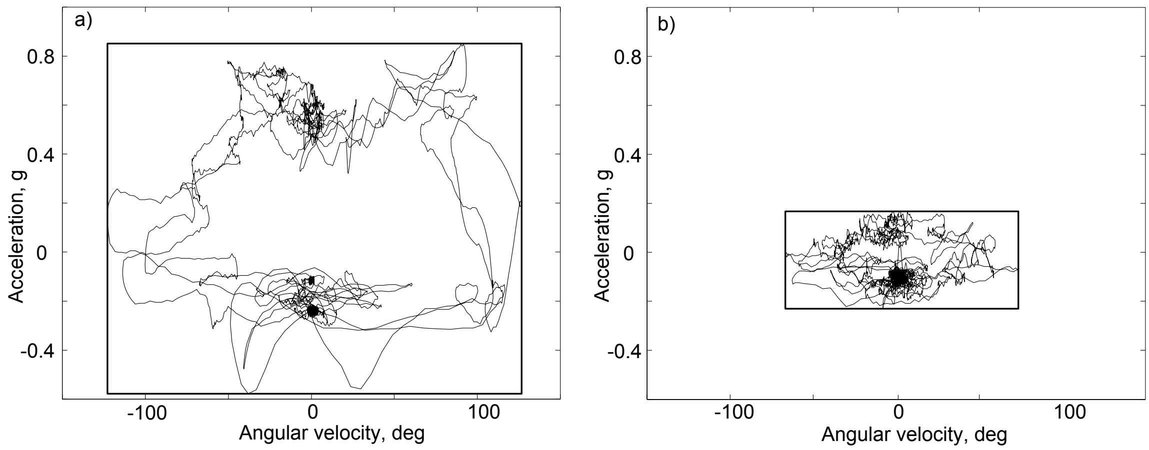

Figure 3.5: Humerus acceleration as a function of its angular velocity for a patient. a) The trace represents the humerus acceleration vs. angular velocity for the healthy side. b) The trace represents the humerus acceleration vs. angular velocity for the painful side. The rectangle, which circumscribes the curve, corresponds to the product of the acceleration range by the angular velocity range (Pr).

We calculated this surface for each axis for both sides and added these to obtain a parameter called Pr for a healthy and a painful side. By considering that the product of the angular velocity and the acceleration is related to the power of the movement, we can therefore assume that P is a power dependent quantity. This parameter can also be considered as the control of the humerus velocity by its acceleration.

The difference between the Pr parameter of a healthy and a painful side relative by the healthy side was considered as ΔPr parameter.

$$\Delta P_r = (P_{healthy} - P_{painful})/P_{healthy} \qquad \text{(Equ. 3.5)}$$

The P score is defined as the average of the ΔPr over all 9 tests.

$$P\ score = 1 - mean\left[\sum_{Test=1}^{9} \Delta\,\mathrm{Pr}\right] * 100[\%] \qquad \text{(Equ. 3.6)}$$

Comparing to RAV where only angular velocities were used, the P score used both the angular velocities and the accelerations of the humerus.

3.2.6 M score algorithm

Our last score considered the difference of moments $\vec{M}$ between the healthy and the painful shoulder; it was based on the angular velocities $\vec{\omega}$ of the humerus and the anthropometrics data of the patient. Van den Bogert et al. expressed the equation of the sum of all moments on a body segment[13]. $\vec{M}$ was defined as the moment of the humerus (Equation 3.7), I as the inertia matrix (Equation 3.8).

$$\vec{M} = I \circ \dot{\vec{\omega}} + \vec{\omega} \times \left(I \circ \vec{\omega} \right) \qquad \text{(Equ. 3.7)}$$

$$I = \begin{bmatrix} Ipitch & 0 & 0 \\ 0 & Iroll & 0 \\ 0 & 0 & Iyaw \end{bmatrix} \qquad \text{(Equ. 3.8)}$$

Using the mathematical definition of the moment of inertia from Vaughan et al.[14] and the anthropometrics data of the patient (length of the humerus: L_h, circumference of the biceps: C_h, mass of the humerus: m), the relationship of the moment of inertia about flexion/extension (*Ipitch*), the moment of inertia about abduction/adduction (*Iyaw*) and the moment of inertia about internal/external rotation (*Iroll*) can be derived.

$$\begin{aligned} Ipitch &= \frac{m \cdot \left(0.076 \cdot C_h^2 + L_h^2\right)}{12} \\ Iroll &= \frac{m \cdot C_h^2}{8 \cdot \pi^2} \\ Iyaw &= Ipitch \end{aligned} \qquad \text{(Equ. 3.9)}$$

We used this method to evaluate the difference between the healthy and the painful shoulder, calculating the maximum of the norm of the moment (noted by || ||) during each test for each shoulder.

$$\Delta M = \max\|M\ healthy\| - \max\|M\ painful\| \quad \text{(Equ. 3.10)}$$

The difference between the healthy and the painful shoulder was expressed as the percentage of the moment of the healthy shoulder.

$$\Delta Mr = \frac{\Delta M}{\max\|Mhealthy\|} \quad \text{(Equ. 3.11)}$$

The M score is defined as the average of the ΔMr over all 9 tests.

$$M\ score = 1 - mean\left\lfloor \sum_{Test=1}^{9} \Delta Mr \right\rfloor * 100[\%] \quad \text{(Equ. 3.12)}$$

A subject with a total mobility of his/her shoulder will have a M score, a RAV score and P score of 100% and a patient without any mobility of his/her shoulder will have a M score, a RAV score and a P score of 0%.

3.2.7 Statistical analysis

The Wilcoxon matched pairs signed rank sum test was used as a non-parametric hypothesis test to show if there were significant differences (at a significance level 5%) between baseline vs. 3 months, and baseline vs. 6 months for 10 patients. The Wilcoxon rank sum test was also used as a non-parametric hypothesis test to show if there were significant differences between baseline vs. 10 control subjects, 3 months vs. 10 control subjects and 6 months vs. 10 control subjects.

To estimate the reliability of the measurements, the interclass correlation (ICC) of the two tests (one year interval) on healthy subjects was calculated for each score.

3.3 Results

3.3.1 Angles estimation

Figure 3.6 shows the angles of the basic movements for the reference system Zebris and the inertial sensors. The proposed method gave an accurate estimation of the shoulder angles. The results of all the tests (Table 3.3) were very close to those of the reference system presenting a small average error in RMS (5.81°), mean (1.80°) and standard deviation (4.82°) of the difference signal, reflecting accurate and precise estimation respectively; and excellent correlation coefficient (0.99) values reflected highly linear response.

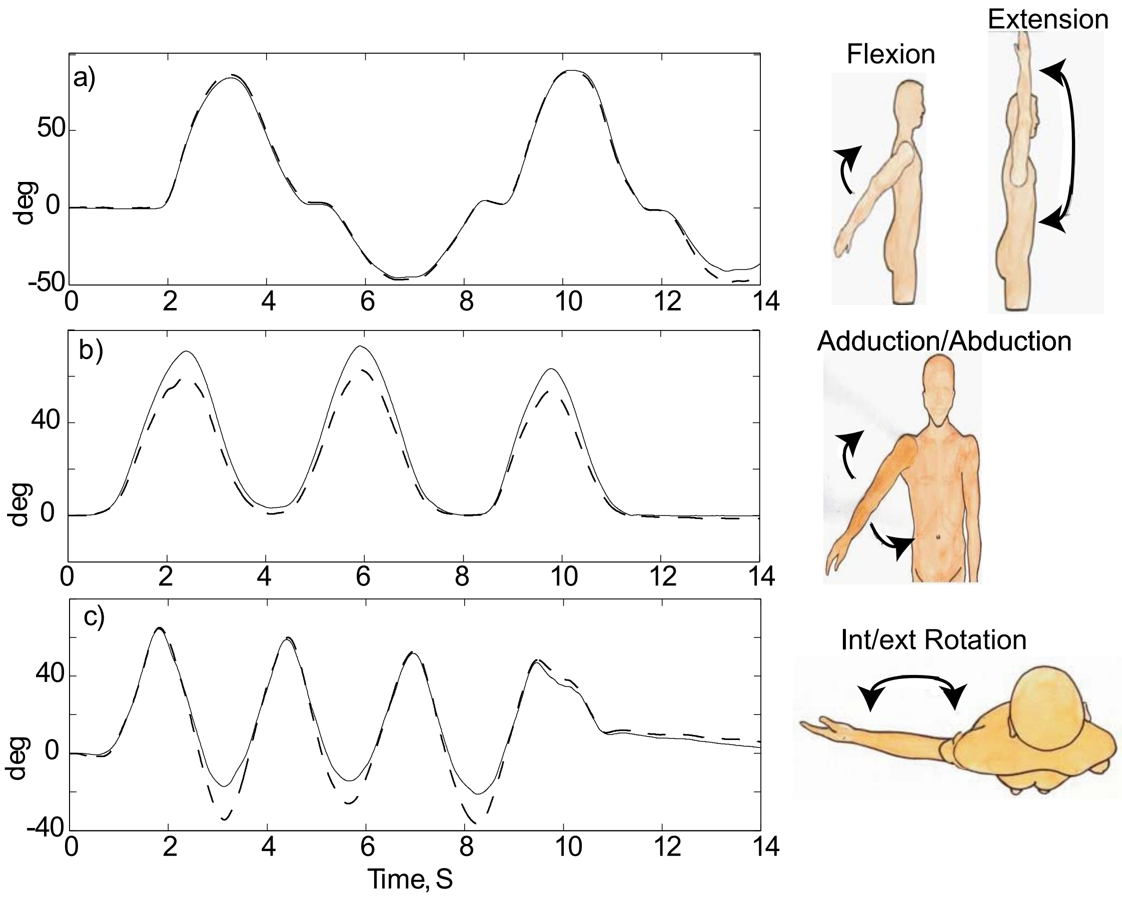

Figure 3.6: Angles estimation compared to the reference system Zebris. a) Flexion, extension. b) Abduction, adduction. c) Internal external rotation. Dashed line: reference system. Solid line: inertial sensors.

Table 3.3: Comparison between the humerus angles obtained by the inertial sensors and the reference system for 10 subjects. The error represents the RMS, mean and SD of the difference between reference and our measuring device. 'r' represents the Correlation Coefficient between the two measuring system.

Subject	Flexion/Elevation Error, deg				Abduction/Adduction Error, deg				Int./Ext rotation Error, deg			
	RMS	mean	SD	r	RMS	mean	SD	r	RMS	mean	SD	r
S1	2.50	-0.45	2.47	0.9986	2.95	-2.20	1.97	0.9968	3.19	0.58	3.13	0.9983
S2	5.64	-3.08	4.72	0.9936	3.83	3.34	1.88	0.9940	2.38	-0.95	2.19	0.9972
S3	4.86	6.25	3.36	0.9888	5.53	-4.08	3.63	0.9994	5.72	-1.90	5.39	0.9865
S4	7.49	6.48	7.29	0.9970	9.61	8.59	6.37	0.9653	8.04	-3.97	6.69	0.9491
S5	7.25	6.02	6.90	0.9945	5.21	2.54	3.63	0.9880	7.99	1.32	7.88	0.9829
S6	7.17	4.40	5.16	0.9953	8.97	6.55	8.52	0.9863	6.25	-5.92	4.61	0.9657
S7	6.59	4.42	5.01	0.9962	1.41	0.48	1.33	0.9993	3.71	-4.49	3.57	0.9739
S8	8.66	2.95	7.16	0.9984	3.62	0.31	3.58	0.9976	5.82	2.25	3.37	0.9950
S9	6.56	5.16	6.44	0.9975	7.80	7.98	5.55	0.9849	6.50	2.68	6.10	0.9971
S10	10.03	4.26	9.09	0.9989	1.12	0.09	1.10	0.9991	7.81	4.32	6.51	0.9933
Mean	6.68	3.64	5.76	0.9959	5.01	2.36	3.76	0.9911	5.74	-0.61	4.94	0.9839

3.3.2 P score

Figures 3.7 a1) and b1) show the comparison of the Pr parameters between a patient and a control subject for the nine realized tests. It can be observed that for the patient (Figure 3.7 (a1)) the P parameter is higher for the healthy side than the painful side for all tests. But for the healthy subject (Figure 3.7 (b1)), the Pr parameter is approximately equal between the right and the left shoulder for each test. Table 3.4 shows the P score for a healthy subject. The P score for the healthy subjects ranged from 85% to 97% (mean: 92%), which is twice compared to patients before surgery (Table 3.4, 3.5).

Table 3.4 shows all the results in comparison with the baseline (before surgery). The Wilcoxon matched pairs signed rank sum test indicates that significant differences were found between the P score at baseline vs. the P score at 3 months and the P score at baseline vs. the P score at 6 months ($p<0.05$).

Table 3.4: DASH, SST, P score, RAV score and M score for patients before surgery (baseline) and 3, 6 months after surgery. NS indicates that no significant differences were found at 5%. The DASH (30 is "very good mobility" and 150 is "very bad mobility"), SST (0 is "very bad mobility" and 12 is "very good mobility")

Patients	1	2	3	4	5	6	7	8	9	10	Wilcoxon Test
Rav Score baseline	42	80	69	70	66	5	50	64	84	59	
Rav Score 3months	87	94	79	98	76	81	62	60	94	76	p=0.0039
Rav Score 6months	87	93	93	94	70	95	54	66	97	76	p=0.0020
P score baseline	28	75	57	62	48	3	36	38	67	48	
P score 3months	70	74	82	91	67	61	42	39	88	59	p=0.0059
P score 6months	76	67	98	93	58	97	33	39	87	69	p=0.0195
M score baseline	22	51	48	42	36	22	15	25	55	25	
M score 3months	64	90	59	37	65	63	31	44	69	64	p=0.0041
M score 6months	66	83	97	44	52	70	23	42	86	60	p=0.0020
Dash baseline	137	91	47	74	93	75	93	128	79	47	
Dash 3months	137	101	34	49	80	74	115	78	50	65	NS
Dash 6months	94	93	34	32	81	54	110	72	54	38	p=0.0273
SST baseline	0	7	9	5	1	5	1	1	4	6	
SST 3months	0	3	11	11	6	6	1	3	5	2	NS
SST 6months	5	4	11	10	6	9	1	3	7	10	p=0.0234

Table 3.5: DASH, SST, P Score, RAV Score and M Score for healthy subjects. For all the healthy subjects : the SST was 12 and the DASH was 30. In brackets: difference between the first measurement and the one year measurement (Δ(1-2)) .

Subjects	P score, %	RAV score, %	M score, %
1	91(7)	94(5)	91(2)
2	96(-12)	99(-14)	87(3)
3	93(-4)	98(-4)	88(3)
4	94(3)	98(-1)	82(2)
5	96(-3)	91(5)	97(-9)
6	93(-11)	95(5)	86(12)
7	97(-13)	95(-8)	95(-15)
8	90(10)	96(1)	93(-3)
9	93(5)	93(6)	72(17)
10	98(-9)	96(-9)	89(5)
Mean Δ(1-2)	-2.7	-1.4	0.7
STD Δ(1-2)	8.5	7.1	9.4
ICC	0.8	0.8	0.78

The P score average was 46%, 67% and 72% respectively at baseline, 3 month and 6 months after surgery. Figure 3.8 a) shows the improvement of the P score after surgery in comparison to the baseline values and the control subjects.

We observed that there were significant differences between the P score at the baseline vs. the P score of the healthy subjects and the P score at 3 month vs. the P score of the healthy subjects, but no significant differences were found between the P score at 6 month vs. the P score of the healthy subjects (p=0.074).

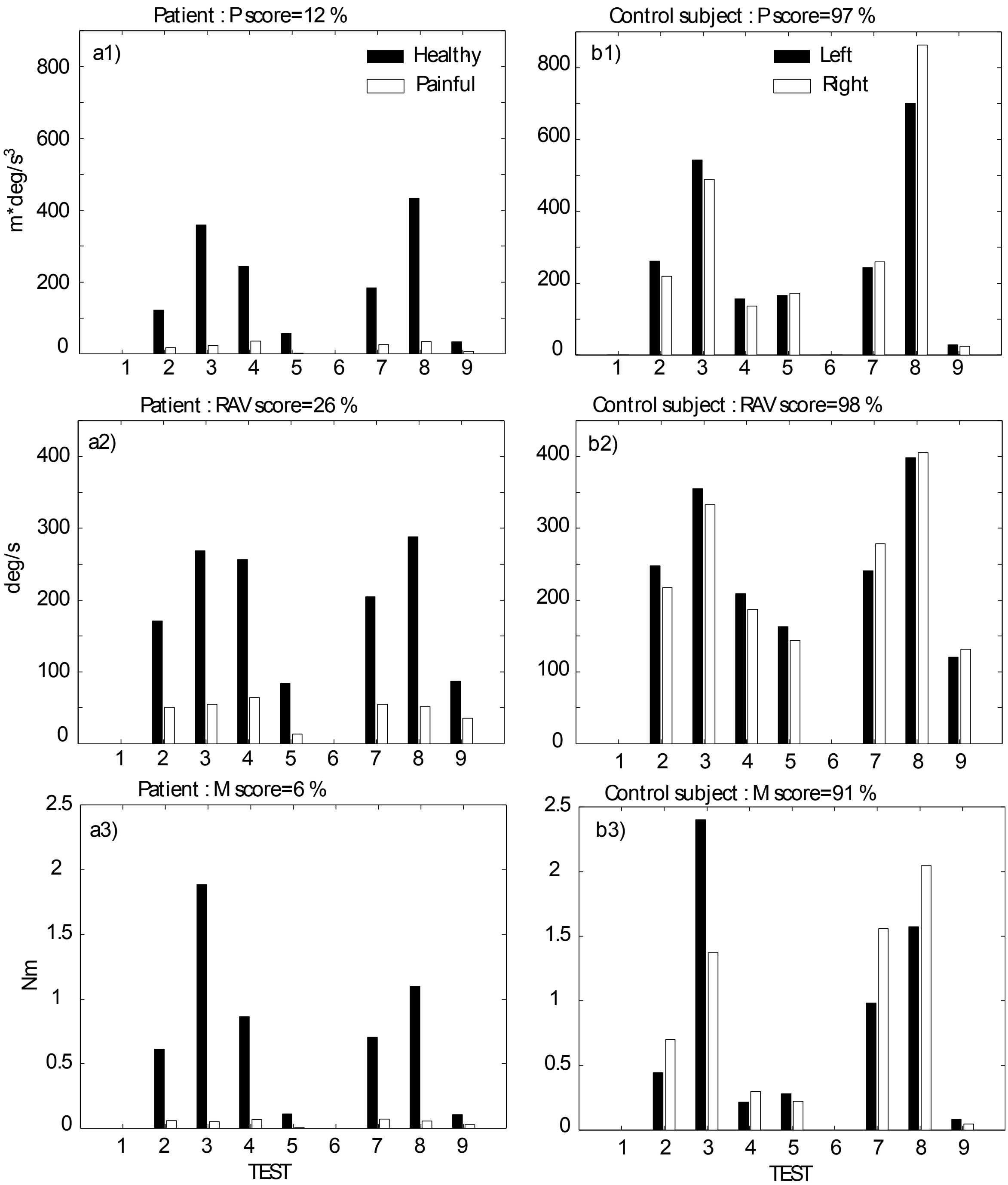

Figure 3.7: Pr parameter for a patient (a1)) and a control subject (b1)). RAVr parameter for a patient (a2)) and a control subject (b2)). Mr parameter for a patient (a3)) and a control subject (b3))

3.3.3 RAV score

Figures 3.7 a2) and b2) show the comparison of the RAV parameters between a patient and a control subject for the nine tests. The RAV parameter is higher for the healthy side than the painful side for all tests (Figure 3.7 (a2)). But for a healthy subject (Figure 3.7 (b2)) the ΔRAV parameter is approximately similar between the right and the left shoulder for each test. The RAV score for the healthy subjects ranged from 87% to 99% (mean: 94%). While this score was in average 59% for patients preoperatively (Tables 3.4, 3.5).

Significant differences were found between the RAV score at baseline and the RAV score at 3 months, as well as between the RAV score at baseline and the RAV score at 6 months ($p<0.05$).

The average of the RAV score was respectively 81% and 83% at 3 months and 6 months after surgery (Table 3.4). Figure 3.8 b) shows the improvement of the RAV score after surgery in comparison to the baseline values and the control subjects.

The RAV score of the healthy subjects was significantly higher than the RAV score at baseline as well as the RAV score at 3 months, but significant differences were also found between the RAV score at 6 months and the RAV score of the healthy subjects ($p=0.037$).

3.3.4 M score

Figure 3.7 a3) and b3) show the comparison of moment in Nm (Newton-meter) between a patient and a control subject for the nine tests. The moments are higher for the healthy side than the painful side for all tests (Figure 3.7 (a3)), while the moments are similar between the right and the left shoulder for a healthy subject (Figure 3.7 (b3)). The M score for a healthy subject ranged from 82% to 97% (mean: 88%), which is more than twice the average for the patients preoperatively (Tables 3.4, 3.5).
The M score at baseline was significantly lower than the M score at 3 months as well as the M score at 6 months ($p<0.05$).

Table 3.4 shows all the results in comparison with the baseline. The M score average was respectively 59% and 62% at 3 months and 6 months after surgery. Figure 3.8 c) shows the improvement of the M score after surgery in comparison to the baseline values and the control subjects. We observed that there were significant differences between the M score at the baseline vs. the M score of the healthy subjects and the M score at 3 month vs. the M score of the healthy subjects, but significant differences were also found between the M score at 6 month vs. the M score of the healthy subjects ($p=0.009$).

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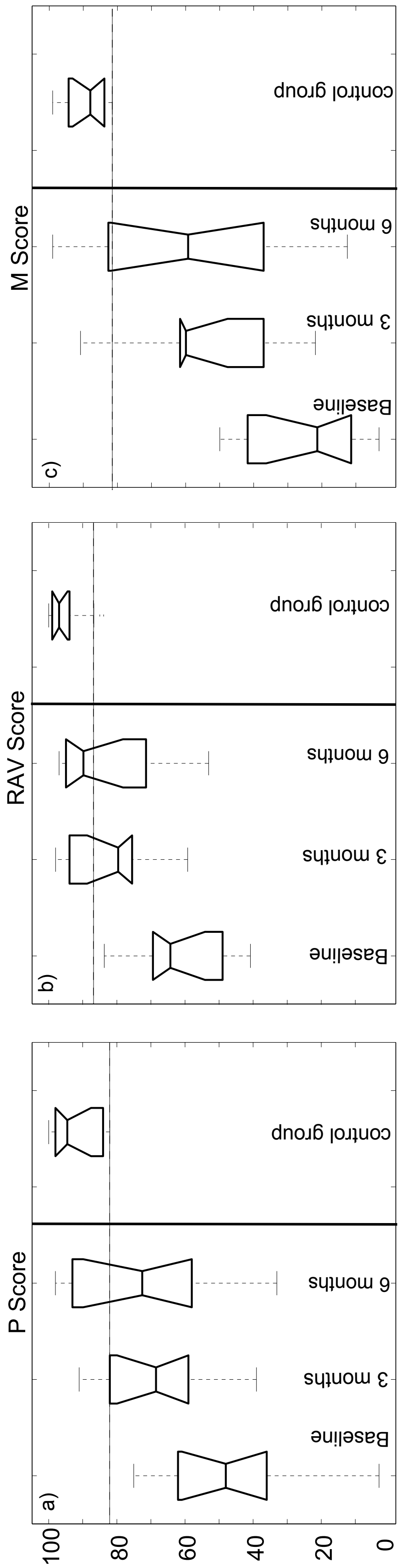

Figure 3.8: Box plot for the P score (a), the RAV score (b) and the M score (c). Boxes contain 50% of the results and lines represent the range. Dashed line show the limit for healthy subjects.

3.4 Discussion and conclusion

Many investigations of the shoulder outcome evaluation previously used the questionnaires and imposed movements. Kirkley et al.[1] presented the differences between scoring systems for the functional assessment of the shoulder. They observed that many of the items may seem irrelevant to patients with specific conditions and none has been accepted as the universal standard. In some case, the patient could not understand the real meaning of the questions and could not answer or answered in a wrong way. The DASH instrument is a questionnaire. It depends on the subjective evaluation of the patients. In some cases, the patient doesn't understand the questions or answers wrongly. It depends also of the patient's psychological condition. Due to the dichotomous response option (yes or no), the SST instrument is likely to have poor differentiation sensitivity between patients with varying severities of the same condition[1].

Our outcome evaluation of the shoulder surgery was based on objectives scores derived from accurate 3D measurements (Table 3.3) of shoulder kinematics on healthy and painful shoulders obtained during specific tasks. These scores concern the acceleration and the angular velocity rather than the components of the angle. Though angles can be estimated accurately with our system, they have not shown pertinent changes between a healthy and a painful shoulder. Figure 3.9 shows the 3D angles for a patient for the test n°2, where the subject moved his hand to the back. The angular ranges are rather larger for the painful side in comparison to the healthy side for the abduction/adduction (yaw) and flexion/extension (pitch) axis. This observation shows that the patient has a strategy to minimize the pain by accomplishing a longer path than normal for the painful shoulder to do the same movement.

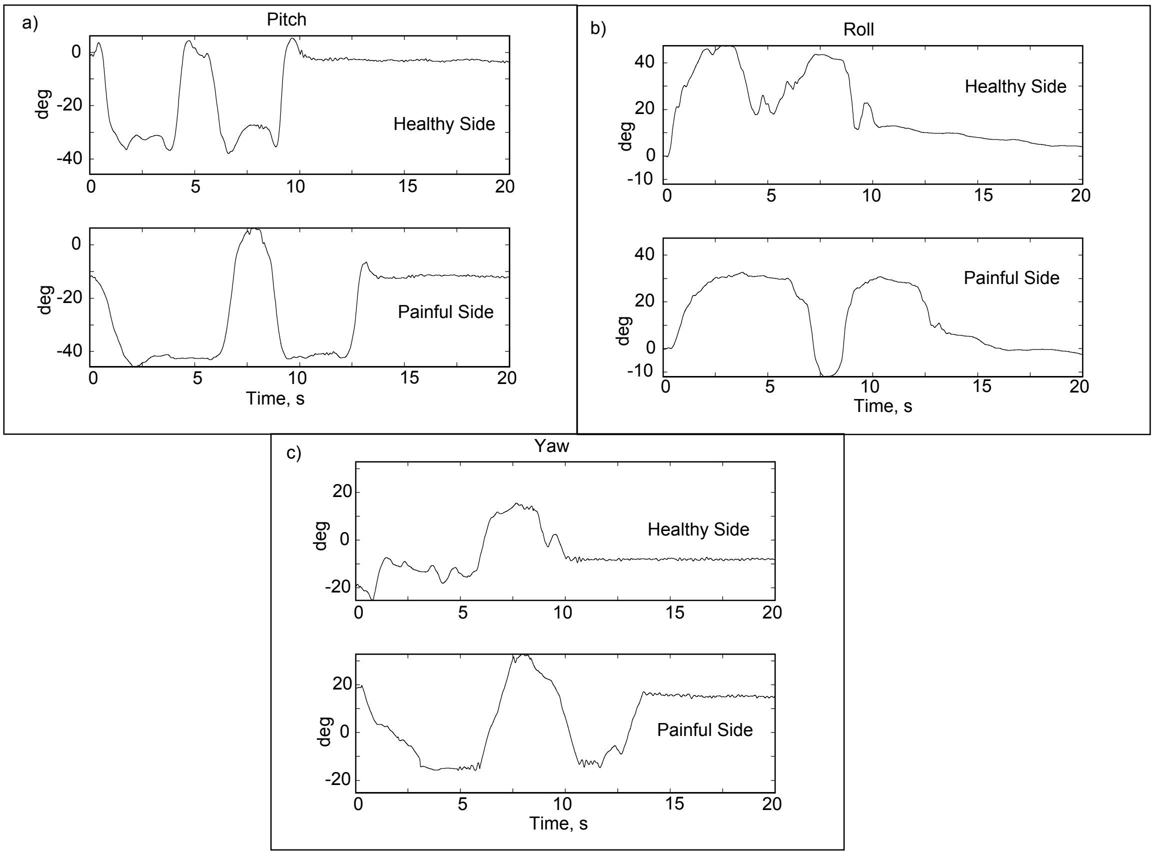

Figure 3.9: Humerus angles for test 2, consisting in moving the hand to the back. Healthy humerus angles and painful humerus angles in flexion/elevation (pitch) (a), in internal /external rotation (roll) (b) and in abduction/adduction (yaw) (c)

However, this is not the case for all patients, since every patient has a different movement strategy to reduce the shoulder pain. Therefore, it was not possible to use the angle magnitude as an objective parameter to quantify the difference between a healthy and a painful shoulder.

This chapter proposed three different scores: the P score based on a combination of accelerations and angular velocities, the RAV score based on the differences of angular velocities range and the M score based on the sum of all moments of the humerus. These scores show a way to assess shoulder function based on a quantification of the difference of kinematics between the healthy and the painful shoulder. Figure 3.8 shows the comparison between baseline, 3 and 6 months after surgery for the three scores. It can be observed with these scores that, for all the patients, the mobility increased significantly after surgery (Table 3.4). In addition, the scores are clearly distinct between a healthy subject and a painful patient at baseline without any overlapping of the confidence intervals (Figure 3.8).

Table 3.4 shows also the results of the Wilcoxon matched pairs signed rank sum test for the clinical scores (DASH, SST). It can be seen that while kinematic scores showed significant differences between baseline and follow-up time ($p<0.02$), the clinical scores (DASH, SST) showed no significant differences between baseline and 3 months evaluation but the differences became significant at 6 months evaluation ($p<0.03$). These results suggested that our inertial scores might be more sensitive to the functional changes than the clinical scores, and were able to express an improvement from the baseline even at 3 months after surgery.

By producing an objective score based on 3D kinematics of the shoulder our system assessed the functionality of the shoulder. However, it can't be used yet for the diagnosis of complex pathologies or to differentiate the pathologies. Our score is not related directly to pain but to the pain's effect on mobility. For example, if a patient experiences pain in a shoulder and therefore moves his shoulder less, our system will detect this lack of functionality. But, in the case where there is no recovery of shoulder functionality even if the pain is removed after surgery, our scores will remain low.

It is noteworthy that those three scores compare the patient's affected and non affected shoulder only if the pathology is unilateral.

Concerning the sensors attachment some precautions should be taken. First, in order to reduce the effects of skin artefacts, a sticking elastic band was used to fix the sensors. In addition, the module was placed on the distal and posterior part of the humerus where there are less skin movement and where sensors can detect all the rotations of the humerus. In fact, if the sensor is positioned at the top of the humerus (near the humeral head), the internal/external rotation cannot be measured.

In order to estimate the repeatability of the system, measurement were repeated on the 10 control subjects after 1 year. The comparison between the two measurements showed a small difference (less than 3% in average with STD less than 10%) with an ICC of 0.8 (Table 3.5).

The proposed scores can be clinically understandable. The RAV score represents the velocity of the humerus. The P score shows how the patient controls the velocity of his humerus using the combination of the accelerations and the angular velocities. The M score represents the sum of all moments on the shoulder. Indeed, our proposed scores are based on the tests corresponding to daily activity (Table 3.1), it can be therefore used in situations where long-term monitoring of shoulder kinematics in daily activity is possible. By recognizing physical activity using additional sensors [17,15] it can be possible to provide a better evaluation of the shoulder mobility and therefore offer a more reliable score since it is based on a natural and voluntary activity of the patients. Moreover using one sensor's module on each humerus and one of the three scores, it could be possible to compare a painful and a healthy shoulder during daily activity (Chapter 7). Monitoring the subjects in their usual environment with minimal interference is therefore possible, in contrast with other systems that require a laboratory.

In the next chapter, we describe how the proposed P score can be used to quantify the dominance of the upper-arm in healthy subjects and patients.

3.5 References

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Chapter 4 Estimating the dominant upper-limb segment during daily activity

***Abstract* –** Considering the results obtained in the chapter 3 for the P score, a new method to quantify the arm dominance and to distinguish a dominant from a non dominant shoulder is presented. An ambulatory system using inertial sensors attached on the humerus was used to differentiate a dominant from a non-dominant shoulder. The method was tested on 31 healthy volunteer subjects without any shoulder pathologies while carrying the system during 8 hours of their daily life. The shoulder mobility based on the angular velocities and the accelerations of the humerus (P score) were calculated and compared every 5 seconds for both sides. Our data showed that the dominant arm of the able-bodied participants was more active than the non dominant arm for standing (+18% for the right-handed, +8% for the left-handed) and sitting (+25% for the right-handed, +18% for the left-handed) postures, while for the walking periods the use of the right and left side was almost equivalent. The proposed method could be used to objectively quantify the upper limb usage during activities of daily living in various shoulder disorders.

4.1 Introduction

Most quantitative approaches to shoulder movement analysis are performed in a laboratory setting where motion captures device such as camera[1], electromagnetic[2], or electromyogram[3,4] systems are used. Although very accurate and important for movement analysis, their use is limited to the volume of the laboratory. There is a difference between what patients can do in a laboratory or a clinical environment and what they actually do in daily life conditions. Consequently the provided information does not reflect the actual body movements as they are during daily activity. Nevertheless, the description of shoulder motion during daily activity is fundamental to better evaluate the consequences of pain on joint mobility and the functional outcome of the patient. When evaluating shoulder motion during daily activities, body fixed sensors, such as inertial sensors, could be used[5].

Several methods have been used to measure shoulder usage using only accelerometers[6,7]. The integrated value of wrist acceleration over a specified period was used to define an index of the amount of movement. Schasfoort et al.[8,9] used a multi accelerometers device including 2 accelerometers on each wrist (sensitive direction perpendicular to the body segment in the sagittal and transversal directions). They presented initial studies for the validity of accelerometry to differentiate usage and non usage upper-limb during a normal life.

Other investigators have used pressure sensors[10,11] to develop a system for the objective measurement of the upper-limb usage during a person's activities of daily living. Their system gave a signal proportional to the vertical displacement of the wrist with respect to the shoulder. They showed that the dominant arm of the ten able-bodied participants was 19% more active than the non dominant arm[10].

While the kind of task tested in a controlled environment such as a laboratory setting is well-known, in activities of daily life, the nature of physical activities where each shoulder is involved is unknown. Since the activity is entirely free, the involvement of the affected shoulder is expected to be different from the healthy shoulder. For a number of shoulder disorders, problems in performing daily activities should be expressed in terms of upper-limb usage. Therefore, we need to quantify the normal shoulder usage in healthy subjects. This way, the shoulder usage in patients with shoulder disorders can be compared to that of normal shoulder usage in order to evaluate shoulder function. Moreover, shoulder usage can be used to evaluate changes in shoulder function overtime, i.e. in baseline and follow-up in order to evaluate the outcome of a treatment.

Many instruments measure upper-limb movement, however, to the best of our knowledge there is no study regarding the differentiation of use of the left or the right shoulder. We have shown in the chapter 3 that the range of movement does not necessarily quantify shoulder function as different movement strategies are often used to compensate for impairments, such as pain. Moreover, the humerus acceleration combined with the humerus angular velocity provides a better score for functional outcome evaluation in patients with shoulder pathology[12]. In this chapter, we use both acceleration and angular velocity of the humerus to introduce an ambulatory method for measuring the usage of shoulders and to quantify the contribution of each shoulder in the patient's daily physical activity. The described method could be used to evaluate the effects of both conservative and surgical shoulder treatments.

4.2 Methods

4.2.1 Subjects and materials

This study received prior ethical approval from the Institutional Ethics Board committee. 31 healthy subjects (mean 32 years old ± 8, 13 women; 23 right-handed, 8 left-handed) were studied. Two inertial modules were fixed by a patch on the dorsal side of the distal humerus and on the thorax (Figure 3.1). This way, the inertial module on the humerus measured the anterior elevation-extension, abduction-adduction and internal-external rotation of the shoulder and the module on the thorax was used to detect daily activities (walking, sitting, standing) using the method proposed by Najafi et al.[12,13]. We have used the monitoring device described in 3.2.1. Each subject carried the system during one day (~8 hours), at home or wherever he/she went. At the end of recording, the data was transferred in a computer for further analysis.

4.2.2 Body posture detection

Body posture allocations (sitting, standing and lying) as well as walking periods were detected by the trunk inertial module[13,14]. The time of sit-stand (respectively stand-sit) transition was detected from the patterns of angular tilt obtained from the gyroscope. Pattern recognition of the vertical acceleration allowed classifying the transition and deciding if the subject was in a standing or a sitting position. The lying position was detected from the inclination of the trunk obtained from the accelerometers. A walking period was defined as an interval with at least three gait cycles. The walking state was identified by analyzing the vertical accelerometer every five seconds. The difference between the right and the left shoulder is shown for each period corresponding to sitting, standing and walking.

4.2.3 Algorithm for estimating dominant shoulder

We have shown in the chapter 3 that the product of range of acceleration and range of angular velocity that inform about the power of the shoulder is a pertinent parameter to evaluate the shoulder mobility. This way a new parameter Pr (Equ. 3.4) was defined that considered the 3D components of acceleration and angular velocity of the humerus obtained from the inertial module fixed on this segment. Pr was estimated every 5 seconds for the left and the right humerus (Pr_{Left}, Pr_{Right}). In order to estimate the shoulder usage, Pr was compared to a defined threshold (thp). If Pr was under thp the humerus was considered motionless, otherwise it was considered active. The periods where Pr > thp were estimated in percent of the total monitoring time and were called Activity. The mean value for Pr (left and right) during the rest position was used to define the optimum thp. If the difference between Pr_{Left} and Pr_{Right} was positive and Pr_{Left} was larger than thp, the usage was classified as a left shoulder usage (ALS=1). If the difference between Pr_{Righ}t and Pr_{Left} was positive and Pr_{Right} was larger than thp, the usage was classified as a right shoulder usage (ARS=1). The percentage of the left shoulder usage (ALSp) and right shoulder usage (ARSp) are described as:

$$ARSp = \frac{\sum_{i=1}^{n} ARS(i)}{n} * 100\%$$

$$ALSp = \frac{\sum_{i=1}^{n} ALS(i)}{n} * 100\% \qquad \text{(Equ. 4.1)}$$

$$n = \text{Total Time of measurement} / 5\,\text{sec}$$

For each interval i of 5 sec, P(i) parameter was defined as :

$$
\begin{aligned}
&\textit{if } \mathrm{Pr}_{\mathrm{Right}}(\mathrm{i}) > \mathrm{Pr}_{\mathrm{Left}}(i) + thp \\
&\quad \mathrm{P(i)} = \mathrm{Pr}_{\mathrm{Right}}(i) \\
&\textit{elseif } \mathrm{Pr}_{Left}(i) > thp \\
&\quad \mathrm{P\ (i)} = -\,\mathrm{Pr}_{\mathrm{Left}}(i) \\
&\textit{else } P(i) = 0
\end{aligned}
\qquad \text{(Equ. 4.2)}
$$

Figure 4.1 shows the flow chart of the shoulder usage estimation.

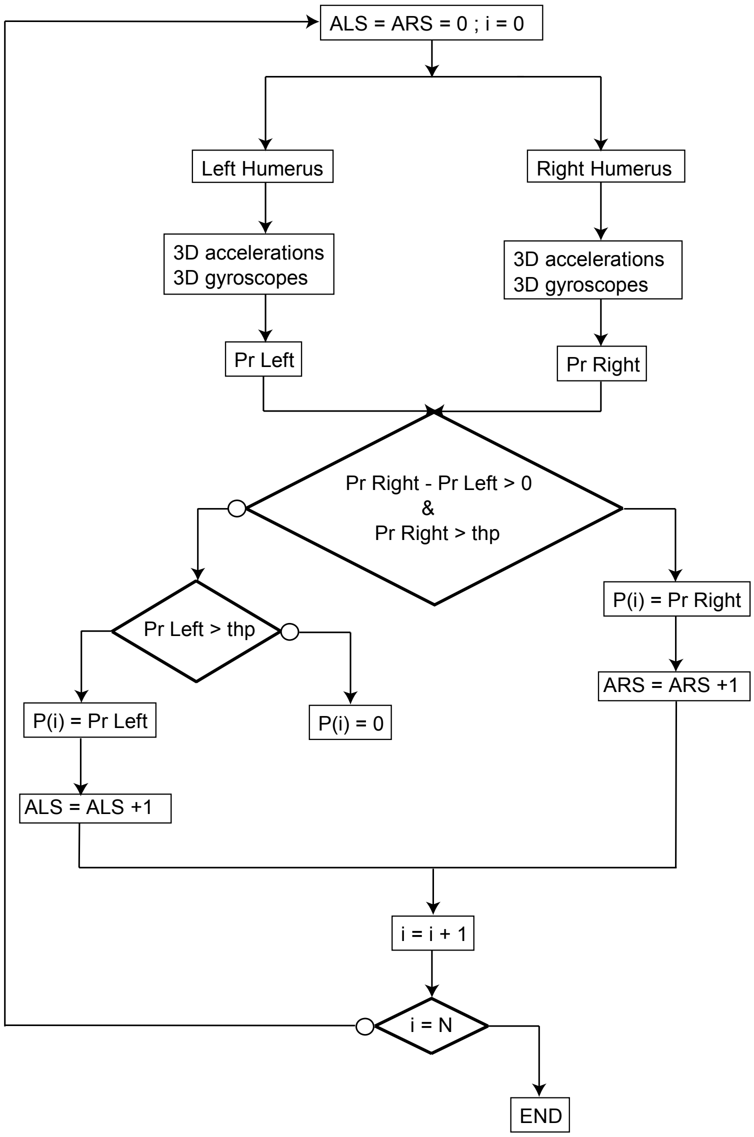

Figure 4.1: Flow chart for estimating the difference between the left and the right shoulder. To obtain the parameter Pr, the acceleration range was multiplied by the angular velocities range each 5 seconds for the left and the right humerus. If the difference between Pr Left and Pr Right is positive and Pr Left is larger than the threshold, the usage is classified as a left shoulder usage (ALS). If the difference between Pr Right and Pr Left is positive and Pr Right is larger than the threshold, the usage is classified as a right shoulder usage (ARS).

4.3 Results

The results for the detection of the different postures (walking, sitting and standing) for a typical patient are presented on the Figure 4.2 (a).

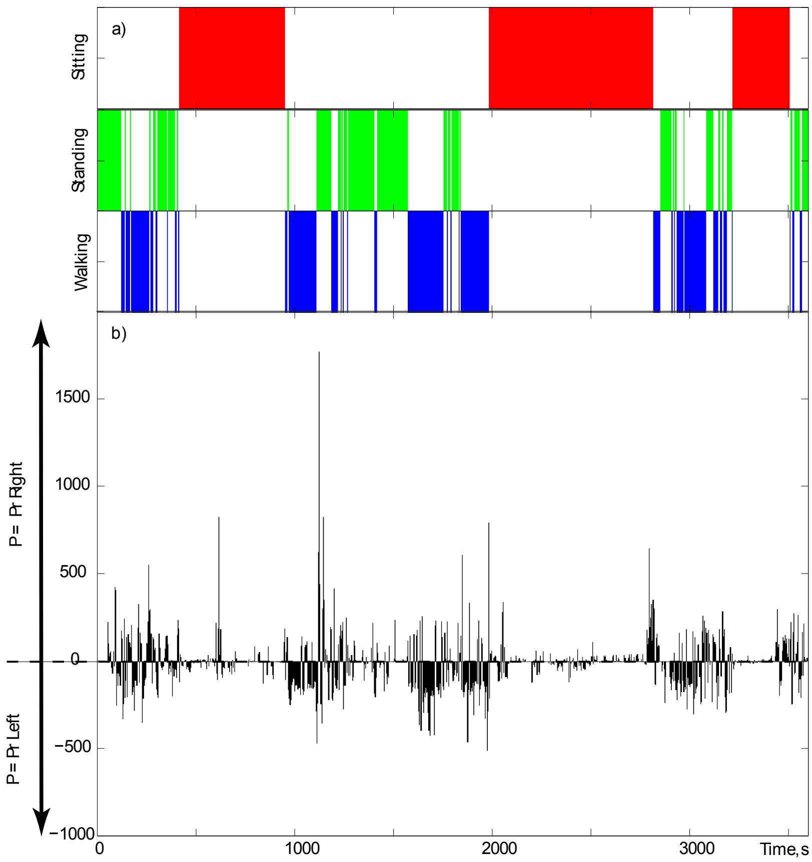

Figure 4.2: (a) Typical physical activity of a left-handed subject classified as sitting, standing, walking during 1 hour of recording. (b) Shoulder mobility expressed by the parameter P for different activity showing clear asymmetry between the left and the right side.

To define the threshold (thp), we turned on the system in rest position during 1 hour to detect the mean value of the Pr for the left and the right humerus. The mean value for Pr_{Left} was 0.859 and the mean value for the Pr_{Right} was 0.556. These values corresponded to the average noise of the motion during rest. Activity periods should be several times above this noise level. To find the optimum threshold, we varied thp from 1 to 10 per step of 1 for the 31 subjects. The optimum threshold was defined as the value where a difference of 1% was observed in the values of ARSp and ALSp (for the sit and stand postures). We obtained an optimum threshold of 3 that was used to estimate the Activity periods. It can be shown in Tables 4.1 and 4.2 that the Activity of both shoulders during standing and sitting postures was 74% and 59% respectively. The Activity of both shoulders during the walk was over 99%.

Table 4.1: Difference between the dominant and the non dominant side for 23 healthy right-handed subjects. Activity for the walk was >99%.

	Walk			Sit			Stand	
Subject	ALSp,%	ARSp,%	ALSp,%	ARSp,%	Activity,%	ALSp,%	ARSp,%	Activity,%
r1	24	76	40	60	60	37	63	69
r2	61	39	45	55	43	45	55	74
r3	58	42	36	64	47	26	74	67
r4	45	55	26	74	50	44	56	63
r5	67	33	33	67	40	44	56	66
r6	54	46	26	74	50	38	62	63
r7	72	28	38	62	58	44	56	80
r8	35	65	40	60	50	47	53	49
r9	60	40	38	52	47	45	55	53
r10	64	36	28	72	46	38	62	33
r11	32	68	31	69	62	32	68	76
r12	45	55	38	62	63	40	60	89
r13	50	50	42	58	57	50	50	76
r14	44	56	38	62	76	37	63	89
r15	42	58	44	56	72	47	53	85
r16	56	44	44	56	69	50	50	84
r17	48	52	46	54	50	40	60	68
r18	42	58	45	55	51	39	61	83
r19	42	58	38	62	86	42	58	94
r20	41	59	37	63	68	38	62	81
r21	57	43	42	58	77	49	51	86
r22	58	42	32	68	71	36	64	87
r23	43	57	34	66	61	35	65	84
Mean	50	50	37	62	59	41	59	74
Std	12	12	6	6	12	6	6	15

Table 4.2: Difference between the dominant and the non dominant side for 8 healthy left-handed subjects

	Walk		Sit			Stand		
Subject	ALSp,%	ARSp,%	ALSp,%	ARSp,%	Activity,%	ALSp,%	ARSp,%	Activity,%
I1	49	51	62	38	82	63	37	93
I2	45	55	52	48	62	48	52	78
I3	39	61	47	53	49	44	56	86
I4	46	54	54	46	64	50	50	72
I5	38	62	49	51	66	52	48	79
I6	63	37	79	21	56	56	44	62
I7	52	48	66	34	69	57	43	78
I8	50	50	60	40	63	60	40	83
Mean	48	52	59	41	64	54	46	79
Std	8	8	11	11	10	6	6	9

The usage of the dominant side (ARSp and ALSp) over the day (8 hours) and during each period of usage is presented for each subject in Tables 4.1 and 4.2. It can be observed that for right-handed subjects (N=23) the right side was in average 18%(±12) and 25%(±12) more used than the left side in standing and sitting postures respectively. While the inverse was occurred for the left-handed subjects (N=8): the right side was in average 8%(±13) and 18%(±21) less used than the left side in standing and sitting postures respectively. For the walking periods, the use of the right side and the left side was almost equivalent (50%-50% for the right-handed subjects; 48%-52% for the left-handed subjects). Data showed that the subjects used their dominant upper-limb for standing and sitting postures in average 18% more than the non-dominant upper-limb (Table 4.1 and 4.2).

The intensity of the shoulder movement expressed by the parameter P is shown in Figure 4.2 for a left-handed subject during 1 hour of recording. The mean of the P parameter during the daily activity for all right-handed subjects was larger for the right shoulder than the left shoulder (Table 4.3). The tendency was inverted for the left-handed subjects in average even if few left-handed subjects had higher intensity for the right shoulder (Table 4.4).

Table 4.3: Difference of movement intensity between the left and the right shoulder for 23 healthy right-handed subjects

	Mean P	
Subject	Left shoulder	Right shoulder
r1	56.5	61
r2	51.2	59.2
r3	53.5	68.2
r4	49.3	65.5
r5	46.7	62.2
r6	53.5	62
r7	57.9	65.4
r8	55.8	79.3
r9	50.5	52.6
r10	62.7	72.7
r11	52.6	64.2
r12	48.2	55.4
r13	56	60
r14	45	53.3
r15	47	51.3
r16	52.6	60.4
r17	50.1	56.9
r18	45.2	53
r19	47.6	54.4
r20	50.1	60.7
r21	49.7	56.2
r22	48.2	60
r23	42.8	55.6
Mean	51.0	60.4
Std	*4.7*	*6.8*

Table 4.4: Difference of movement intensity between the left and the right shoulder for 8 healthy left-handed subjects

	Mean P	
Subject	Left shoulder	Right shoulder
l1	51.5	42.8
l2	57.5	55
l3	45.7	48
l4	57.7	53
l5	50.9	51.2
l6	53.9	56.3
l7	54	48.8
l8	55.7	46.9
Mean	53.4	50.3
Std	4.0	4.5

4.4 Discussion and conclusion

We have proposed an ambulatory method to evaluate the usage and non usage of upper limbs during daily physical activity. Based on 3D inertial sensors on both humerus, our method can quantify the difference between the dominant and the non-dominant shoulder for a healthy subject for his/her different postures. The figure 4.2 shows that the intensity of the movements of the shoulders is not similar for each posture. In this fact, we decided to separate the usage of the shoulders in gait, standing and sitting postures. Data showed that the left shoulder and the right shoulder have the same rate of usage for the left-handed and right-handed subjects during walking but for the standing and sitting postures we are able to differentiate quantitatively the left-handed from the right-handed subjects ($p<0.00053$) (Table 4.1 and 4.2). Actually, during the walk, the upper-limbs have a cyclic movement. During the sitting and standing postures, by using his/her dominant side, the subject leaves the non dominant side inactive or in posture to stabilize the movement. This could explain the difference between the dominant and the non dominant shoulder activity. Although walking solicited both arms equally during the whole walking period, it can not be concluded that during each period of walking, the left and the right arms have the same rate (as it can be seen in Figure 4.2). For example, external work (carrying a load) could affect this similarity. However, it is not yet possible to automatically determine whether a subject is performing ordinary walking or carrying a bag while walking. Calibrating the ordinary walking of a subject at the beginning of a measurement period or using electromyogram (EMG) recordings may be a solution. Therefore, with the proposed method, the quantification of the shoulder mobility in regards to the physical activity can provide a better insight of a patient's recovery after treatment. The goal of the study focused only on the shoulder constraints, not on the forearm or the hand. We did not study the hand dominance, but the arm and shoulder dominance.

The intensity of the upper-limb movement was estimated using the parameter P that considers 3D kinematics (accelerations and angular velocity) of the shoulder. The sensitivity of this parameter to show shoulder function improvement has already been shown in the previous chapter.

Our method was sensitive to the movements on the horizontal plane and a difference of the usage's rate is shown between the standing and the sitting postures. Both shoulders were more active (+18%) during the standing posture than the sitting posture (Tables 4.1 and 4.2). Moreover, the mean P parameter is significantly different for the dominant shoulder than for the non dominant shoulder ($p<0.004$) (Tables 4.3 and 4.4).

These results will be used on patients with pathologies of the shoulder in chapter 7. As example, the Figure 4.3 shows the evaluation of the dominant shoulder for a typical right-handed patient with a right painful shoulder (rotator cuff disease). For this patient, the functionality of his right shoulder (dominant) was less than his left shoulder (non dominant). His usage corresponded rather to the left-handed subjects (Table 2). This tendency will be discussed in the chapter 7 (7.2.4.2).

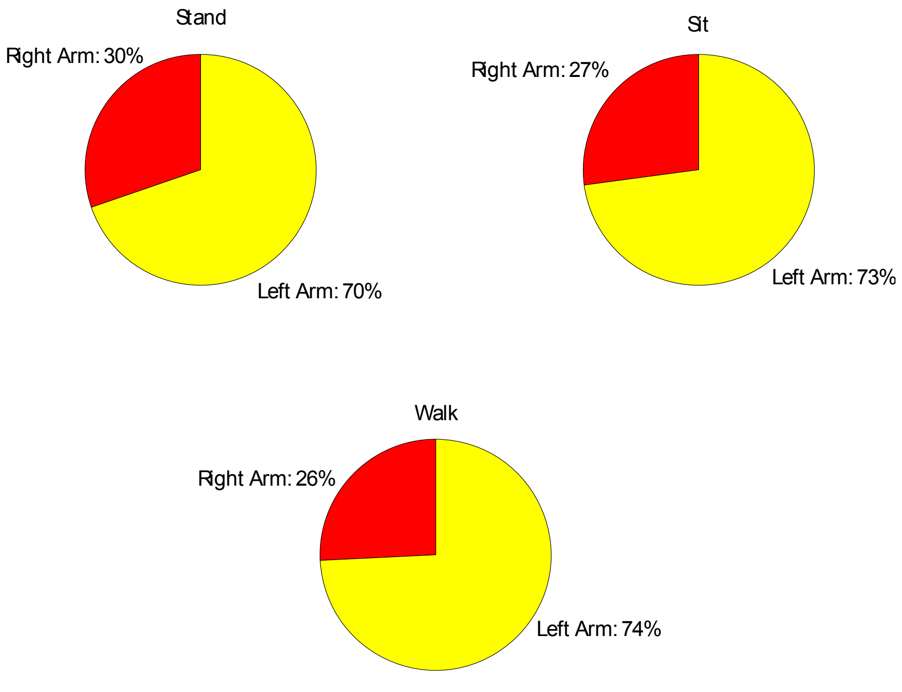

Figure 4.3: Estimation of the dominant shoulder for a typical right-handed patient with his right painful shoulder before surgery during the standing, sitting and walking activity.

Based on kinematics of the subjects, we were able to find the difference between the dominant and the non dominant shoulder and quantify if a person is right-handed or left-handed during daily activity. This study provides preliminary evidence that this system is a useful tool for objectively assessing the upper-limb usage during daily activity. The proposed system was used during daily activity for patients with shoulder disorders (Chapter 7). Although the intensity of the movement as estimated by the P score in this chapter is important, it does not provide the frequency (e.g the number of flexions per hour) of the movement. This is the aim of the next chapter, where the type of the movement and its frequency for the dominant and the non dominant humerus is estimated.

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Chapter 5 Characterization of the movement of the humerus during long-term measurements

Abstract - A new method of recognizing the movement of the humerus is presented. 3D gyroscopes attached on the humerus were used to identify the movement of flexion-extension, abduction-adduction and internal/external rotations of the humerus. Within each identified movement the rates of adjunct (deliberate rotation of the joint) and conjunct rotations (inherent or automatic rotation of the joint) were also estimated. The method was validated in laboratory setting and then tested on 31 healthy volunteer subjects without any shoulder pathologies while carrying the system during ~8 hours of their daily life. Based on the comparison of the angular velocities, we were able to find the frequency (number/hour) of each movement during daily activity, the rate of adjunct and conjunct rotations for each movement and the frequency of humerus over slow, medium and fast movement. The results showed that the number of movements per hour was highest for walking and significantly lowest for sitting posture ($p<0.008$). Moreover, during the whole daily activity and for each posture (i.e. walking, sitting and walking) the number of internal/external rotations was significantly highest while the number of abductions-adductions was the lowest ($p<0.009$). Despite of the difference observed on the number of movements the rate of conjunct and adjunct rotations were quite similar for all subjects within each movement: flexion-extension was composed of 48% of pure flexion, 19 % of pure abduction and 33% of pure int/ext rotation, the abduction-adduction was composed of 45% of pure abduction, 22% of pure flexion and 33 % of pure int/ext rotation and the internal/external rotation was composed of 61% of int/ext rotation, 22% of pure flexion and 17% of pure abduction. These results will be very useful for the future studies on patients with pathologies of the shoulder.

5.1 Introduction

In the chapter 4, we described a method to distinguish the dominant from the non dominant shoulder during daily activity. In the present chapter, a method to characterize the kind of movements of the dominant and the non dominant shoulder is presented. Shoulder movements are composed of adjunct and conjunct rotations[1]. The adjunct rotation corresponds to deliberate rotation of the joint while the conjunct rotation is the inherent or automatic rotation of the joint. The conjunct rotations are due to anatomic reasons and the tensions of ligaments and muscles[1]. There is a general agreement that patients with rotator cuff impingement, adhesive capsulitis or glenohumeral degenerative diseases have a diminished arm flexion, abduction or internal/external rotation. In spite of the recourse to careful and complex studies, a precise evaluation of the shoulder movement based on the estimation of the number of movement per hour and the quantification of adjunct and conjunct rotation is still missing.

The goal of this chapter was two-fold. First, validating an algorithm for the detection of the type of shoulder movement (flexion-extension, abduction-adduction and internal/external rotations) and the ratios of the adjunct and conjunct rotations for each movement. The second goal was to evaluate the effectiveness of this algorithm during long term measurements. By validating such an approach, we will provide a clinical tool that can be used to assess the shoulder's function and to find objective scores for outcome evaluation of a shoulder pathology treatment.

5.2 Methods

5.2.1 Subjects and materials

31 healthy subjects (32 years old ± 8; 18 men, 13 women; 23 right handed, 8 left handed) were studied. In this study, two inertial modules with 3D gyroscopes were fixed by a patch on each dorsal side of the distal humerus and one module with 3D gyroscopes and 3D accelerometers on the thorax (Figure 3.1). The sensors on the humerus measured the

anterior flexion-extension (pitch), abduction-adduction (yaw) and internal-external rotation (roll) of the shoulder and the module on thorax was used for detecting daily activities (walking, sitting, standing) using the method proposed by Najafi et al.[2,3] (Chapter 4, 4.2.2 Body posture detection).

5.2.2 Detection of adjunct and conjunct rotation of the humerus movements

3D angular velocities of the humerus were used to detect the movement and its axis of rotation. The pitch, roll and yaw angular velocities were associated to the local coordinate systems, segments and joint rotation according to the ISB standardization proposal for the upper extremity[4] (Figure 5.1).

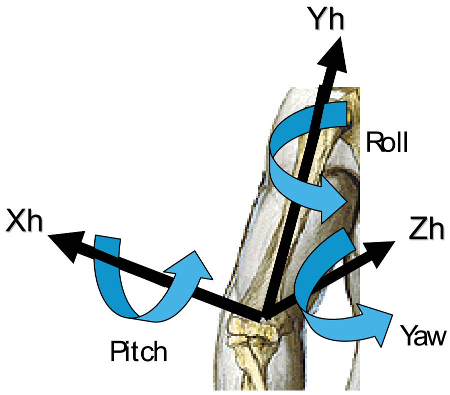

Figure 5.1: Local coordinate systems of the humerus for the angular velocities (roll, pitch, yaw). Adapted from ISG standardization proposal for upper extremity.

Figure 5.2 shows the three angular velocities recorded respectively for a flexion movement of 90°, an abduction of 90° and an internal/external rotation of 90°. During the flexion, the range the pitch angular velocity was higher than the two other components (yaw and roll). Similar results can be observed for internal/external rotation (i.e. the range of the roll angular velocity was higher than yaw and pitch components) and for abduction (i.e. the range of the yaw angular velocity was higher that pitch and roll components). We assumed therefore that the angular velocity with higher amplitude defines the type of adjunct rotation while the other lower components of angular velocity belong to conjunct rotations.

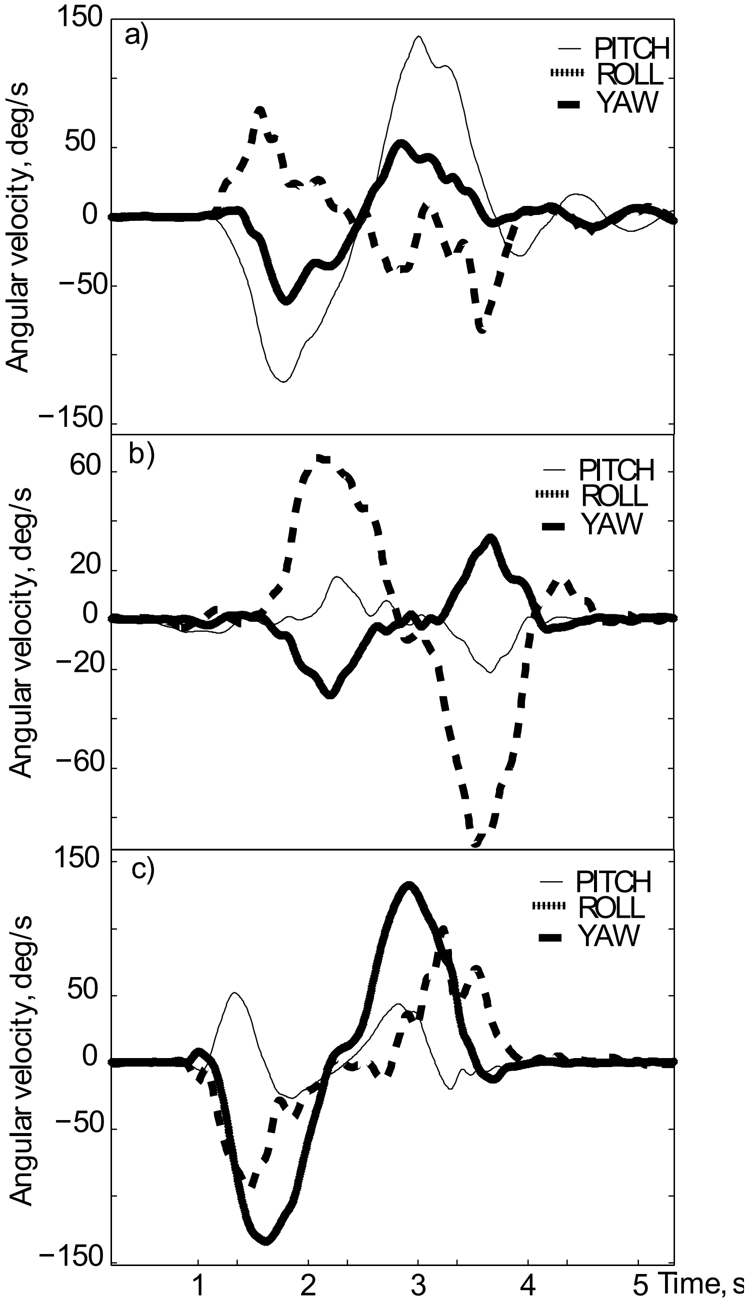

Figure 5.2: Angular velocities (Pitch, Roll, Yaw) from the kinematics sensors for the flexion (a), the internal/external rotation (b) and the abduction (c).

To detect the shoulder movement, the absolute values of each component of angular velocity (pitch, roll, and yaw) was compared to a threshold (th). The shoulder was considered in movement if at least one component of angular velocity was higher that th. Then, the component of angular velocity with highest absolute angular velocity was considered as adjunct rotation. If the adjunct rotation was pitch the movement was defined as a flexion-extension (FE). Similarly, if the adjunct rotation was yaw, the movement was defined as abduction-adduction (AA), and if the adjunct rotation was roll, the movement was defined as internal/external rotation (IE). The amplitude of each rotation (A_{FE}, A_{AA}, and A_{IE}) was divided by the sum of the amplitude of all rotations (i.e. adjunct and conjunct) and expressed in percentage:

$$FE = \frac{A_{FE}}{A_{FE} + A_{AA} + A_{IE}};\ AA = \frac{A_{AA}}{A_{FE} + A_{AA} + A_{IE}};\ IE = \frac{A_{IE}}{A_{FE} + A_{AA} + A_{IE}} \qquad \text{(Equ. 5.1)}$$

For example: an abduction movement expressed in FE/AA/IE percentage as 20/45/35 represents 45% adjunct rotation and 20% and 35% conjunct rotations while a “pure” flexion could be represented by 100/0/0 in FE/AA/IE.

The threshold (th) was necessary to avoid the noise of the gyroscopes at rest and to decrease the false detections of the movement. The threshold (th) was adapted (adaptive threshold) every hour during the recording and was estimated for each subject and each humerus. To define th, we searched during each hour of recording all the positive peaks for each of the three angular velocities higher than 10°/s (almost still period of humerus). For each angular velocity, we calculated the average of the peaks. The threshold (th) was fixed to the minimum value of these averages.

5.2.3 Validation

During the validation part, the 31 subjects carried the system and were asked to perform flexion, abduction and internal/external rotation with both arms while in hospital. To estimate the performance of the rotation classification, the sensitivity (defined as the ability of the system to correctly identify the true rotation) and the specificity (defined as the ability of the system to not generate false detection) were estimated. The sensitivity and the specificity were calculated as follow.

Sensitivity was defined as:

$$\frac{\text{True Positive (TP)}}{\text{True Positive (TP)} + \text{False Negative (FN)}} \times 100\% \qquad \text{(Equ. 5.2)}$$

Specificity was defined as:

$$\frac{\text{True Negative (TN)}}{\text{True Negative (TN)} + \text{False Positive (FP)}} \times 100\% \qquad \text{(Equ. 5.3)}$$

For example, for the flexion movements, the above parameters were defined as follow: the true positives were the numbers of true flexion detected by the algorithm. The false negatives were the numbers of undetected flexion. The true negatives were the numbers of other type of movement detected by the algorithm, which are not true flexion. The false positives were the numbers of false detection as flexion.

5.2.4 Long-term measurement

Each subject carried the system during one day (~8 hours), at home or wherever he/she goes. At the end of recording data were transferred to computer for further analysis. Using the algorithm described in 5.2.2 and the validation in 5.2.3, the type of the movement was detected. Then, the following parameters were estimated:

- The number of movements recognized as flexion-extension (N_{FE}), abduction-adduction (N_{AA}) and internal/external rotation (N_{IE}) per hour and for each posture allocation.
- The percentage of adjunct and conjunct rotation for each detected movement: FE/AA/IE.
- The number of movements over three range of angular velocities: slow (less than 50 °/s), medium (between 50°/s and 100°/s) and fast (higher than 100°/s).

5.2.5 Statistical analysis

The Wilcoxon unmatched pairs signed rank sum test was used as a non-parametric hypothesis test to show if there were significant differences (at a significance level of 5%) between the number of movements, the combination of adjunct and the conjunct rotation for the left and right shoulder.

5.3 Results

5.3.1 Results of the validation phase

Table 5.1 shows the specificity and sensitivity of the flexion, abduction and internal/external rotations for the adaptive threshold (th). The specificities were 100% for the flexion and the internal/external rotation, the sensibilities were 100% for the abduction and the internal/external rotation. But the sensitivity was 94% for the flexion and the specificity was 97% for the abduction. For comparison, we have also reported the results obtained with a minimum threshold of 10 deg/s and a fixed threshold of 33 deg/s. which corresponded to the average of all adaptive thresholds obtained during long-term recording.

Table 5.1: Specificity and Sensitivity for the detection of the flexion, abduction and internal/external rotation. TP: true positive; TN: true negative; FP: false positive; FN: false negative.

Rotation	TP	TN	FP	FN	Sensitivity, %	Specificity, %
th = 10°/s						
Flexion	31	123	7	34	47	95
Abduction	24	102	28	41	37	78
Int/ext Rotation	56	81	49	9	86	62
th = 33°/s						
Flexion	41	122	8	24	63	94
Abduction	36	108	22	29	55	83
Int/ext Rotation	61	107	23	4	94	82
Adaptative threshold						
Flexion	58	124	0	4	94	100
Abduction	62	120	4	0	100	97
Int/ext Rotation	62	124	0	0	100	100

5.3.2 Results of the long-term measurement

For each subject, walking, sitting and standing periods were recognized over a day (~8 hours) and for each period the number of flexions, abductions and internal/external rotations movements normalized by the time of each posture were estimated for each humerus (N_{FE}, N_{AA}, N_{IE}). All results are reported in Tables 5.2-5.5 for right handed and left handed subjects.

Table 5.2: Number of flexions, abductions and int/ext rotations per hour for all activities for the right handed subjects.

	N_{FE}		N_{AA}		N_{IE}	
Subject	right	left	right	left	right	left
r1	157	121	73	47	272	259
r2	150	181	76	59	291	273
r3	129	105	44	35	209	168
r4	124	109	59	70	301	244
r5	87	95	54	40	251	188
r6	123	72	37	33	213	113
r7	136	189	90	56	298	274
r8	99	96	38	38	237	219
r9	131	119	36	35	185	165
r10	86	68	39	33	160	103
r11	165	154	68	57	309	213
r12	215	199	96	109	476	444
r13	161	122	69	87	308	306
r14	246	222	140	139	521	473
r15	210	175	81	102	406	388
r16	153	173	77	65	406	310
r17	134	139	66	53	311	283
r18	205	146	80	67	420	396
r19	252	287	152	103	492	476
r20	183	150	93	70	333	322
r21	210	229	112	114	534	503
r22	196	176	104	80	438	377
r23	234	224	87	97	539	491
Mean	165	154	77	69	344	304
Std	49	55	31	30	116	122

Table 5.3: Number of flexions, abductions and int/ext rotations per hour for all activities for the left handed subjects

	N_{FE}		N_{AA}		N_{IE}	
Subject	right	left	right	left	right	left
I1	156	209	86	112	325	342
I2	129	129	70	65	306	326
I3	206	163	83	90	396	407
I4	141	146	68	95	270	270
I5	200	169	89	94	388	408
I6	79	93	47	50	190	198
I7	245	265	98	141	360	376
I8	201	244	99	107	388	406
Mean	170	177	80	94	328	342
Std	53	58	17	28	71	75

Table 5.4: Number of flexions, abductions and internal/external rotations per hour for the right handed subjects

	Walk						Sit						Stand					
	N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}	
Subject	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left
r1	464	280	250	175	795	822	113	89	52	25	210	178	142	122	60	45	231	234
r2	349	493	206	145	708	693	72	92	29	27	133	119	132	133	66	52	255	236
r3	378	568	209	127	745	779	97	47	19	22	129	83	143	119	57	41	253	204
r4	380	373	184	288	747	740	67	52	35	30	199	119	103	89	42	47	246	226
r5	332	450	283	180	799	807	34	27	13	16	129	60	70	65	33	23	205	148
r6	723	668	231	296	919	863	82	31	27	16	156	55	114	75	25	30	219	130
r7	349	581	256	140	765	816	83	98	43	27	152	120	104	139	78	52	267	239
r8	396	244	175	137	697	758	75	80	27	33	213	187	85	89	31	28	182	170
r9	712	688	261	204	856	872	47	46	11	14	91	67	115	96	24	27	163	140
r10	496	541	341	343	805	812	70	34	25	11	111	42	41	30	10	9	101	52
r11	590	607	251	260	858	759	94	80	43	34	206	112	160	149	56	39	303	224
r12	440	426	204	288	837	841	88	100	31	35	259	203	187	153	88	83	403	388
r13	498	396	201	318	871	898	95	66	44	39	185	170	163	127	66	96	321	332
r14	424	440	265	269	783	808	136	101	60	69	301	232	165	140	93	88	378	331
r15	484	389	207	233	778	751	99	87	31	37	224	193	131	111	49	73	286	284
r16	531	607	252	184	830	883	87	108	40	34	301	201	140	144	76	68	386	285
r17	530	564	254	184	822	863	46	39	21	18	142	109	96	103	51	42	275	243
r18	361	261	125	104	716	680	90	63	34	29	203	184	131	91	57	48	269	254
r19	544	597	272	216	878	889	102	117	80	46	251	209	188	218	120	77	389	378
r20	604	559	265	219	878	841	79	58	38	32	179	165	132	99	82	52	261	265
r21	440	471	239	211	862	886	119	133	61	58	356	283	156	171	84	93	432	412
r22	412	434	242	184	843	793	124	96	60	49	266	199	182	166	99	73	440	398
r23	416	466	160	199	877	900	109	90	31	25	262	196	173	155	66	71	415	366
Mean	472	483	232	213	812	815	87	75	37	32	202	152	133	121	61	55	290	258
Std	109	124	46	65	61	64	25	30	17	14	68	64	38	41	27	24	92	95

Table 5.5: Number of flexions, abductions and internal/external rotations per hour for the left handed subjects

	Walk						Sit						Stand					
	N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}	
Subject	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left
I1	560	591	290	281	827	825	118	188	53	102	276	315	165	232	98	130	382	399
I2	393	387	178	189	785	775	81	84	47	41	200	220	113	108	66	59	294	319
I3	512	439	237	262	853	789	52	38	21	19	117	123	164	123	57	64	339	369
I4	584	657	325	332	866	876	93	101	37	82	194	212	128	118	64	76	274	250
I5	546	403	193	229	860	886	95	98	48	41	194	217	137	120	69	73	304	317
I6	236	379	210	198	687	792	43	44	21	25	101	96	126	120	56	67	260	260
I7	543	544	198	195	721	693	89	174	47	77	184	241	218	212	87	149	319	327
I8	563	589	309	205	859	822	81	93	37	47	168	216	162	225	74	107	360	362
Mean	492	499	242	236	807	807	82	103	39	54	179	205	152	157	72	90	316	325
Std	119	109	57	51	70	61	24	54	12	30	54	68	33	55	15	34	42	52

Typical results obtained for the subject r7 over a day are illustrated in Figure 5.3 where for each activity (i.e. walking, sitting and standing) the occurrence of different movement of the right humerus can be observed.

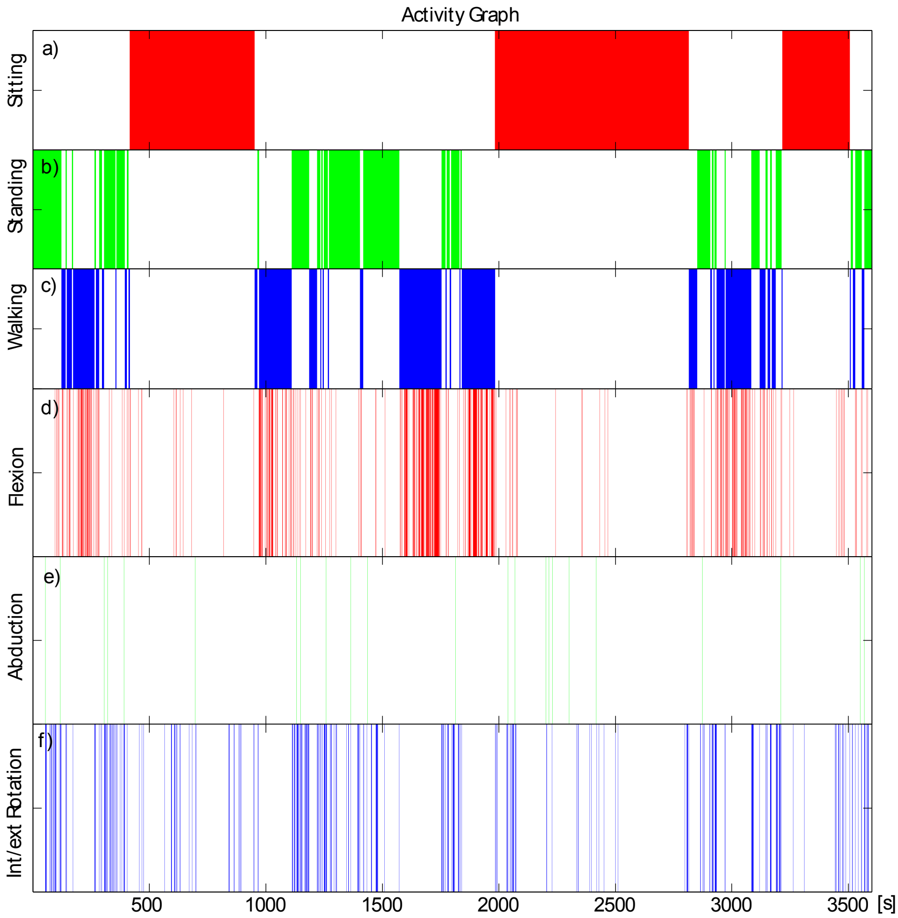

Figure 5.3: Typical classification of a subject's physical activity during a 1h recording (a) sitting, (b) standing, (c) walking, (d) flexion, (e) abduction and (f) internal/external rotation for the right humerus.

We counted more movements per hour in average on the right humerus (flexion right: 165; flexion left: 154; abduction right: 77; abduction left: 69; internal/external rotation right:344; internal/external rotation left:304) for the right handed subjects (N=23). While the inverse was occurred for the left handed subjects (N=8) (flexion right: 170; flexion left: 177; abduction right: 80; abduction left: 94; internal/external rotation right:328; internal/external rotation left:342) (Table 5.2 and 5.3). However, statistical tests showed that dominant shoulder and non dominant shoulder had no significant difference (p>0.1) for the number of flexions (N_{FE}), abductions (N_{AA}) and internal/external rotations (N_{IE}) per hour for the sitting and standing posture (Table 5.4 and 5.5). Moreover, there was no significant difference (p>0.3) between the dominant and the non dominant shoulder during the gait.

The number of movements was significantly higher for walking compared to sitting and standing and the number of standing was significantly higher than that of sitting (p<0.008). For all postures, as well as during the whole daily activity, we found a significantly highest number of movements per hour for the internal/external rotations and the lowest number of movements per hour for the abductions-adductions (p<0.009).

Table 5.6: The combination of adjuncts and conjuncts rotations for the right handed subjects and the difference Δ between right and left humerus.

	Flexion			Abduction			Int/ext Rotation		
Subject	Right FE/AA/IE	Left FE/AA/IE	Δ	Right P/Y/R	Left FE/AA/IE	Δ	Right FE/AA/IE	Left FE/AA/IE	Δ
r1	50/20/30	50/20/30	0/0/0	24/46/30	23/43/34	-1/-3/4	21/18/61	20/18/62	-1/0/1
r2	47/19/33	51/17/31	4/-2/-2	23/44/34	24/46/30	1/2/-4	23/17/60	25/16/59	2/-1/-1
r3	51/20/29	53/18/28	2/-2/-1	20/49/31	23/48/29	3/-1/-2	21/18/61	22/17/61	1/-1/0
r4	47/20/32	46/21/33	-1/1/1	23/42/35	23/43/34	0/1/-1	20/17/63	19/18/62	-1/1/-1
r5	47/21/33	47/17/36	0/-4/3	25/40/35	26/42/32	1/2/-3	19/18/63	23/16/62	4/-2/-1
r6	50/21/29	49/20/31	-1/-1/2	24/46/30	25/43/31	1/-3/1	22/18/60	24/17/58	2/-1/-2
r7	46/21/33	50/18/32	4/-3/-1	20/46/33	24/47/29	4/1/-4	20/20/60	24/17/59	4/-3/-1
r8	49/19/32	49/21/31	0/2/-1	24/48/28	23/45/32	-1/-3/4	25/16/62	19/18/63	-3/2/1
r9	51/17/32	51/18/31	0/1/-1	25/47/28	26/45/29	1/-2/1	21/16/59	26/16/59	1/0/-0
r10	49/20/31	47/22/31	-2/2/0	23/42/35	29/39/33	6/-3/-2	23/17/62	25/16/59	4/-1/-3
r11	50/18/32	52/19/29	2/1/-3	22/45/32	24/46/31	2/1/-1	22/17/61	26/17/57	3/-1/-4
r12	45/18/35	46/20/34	1/2/-1	23/41/36	23/42/34	0/1/-2	25/17/62	21/17/62	-1/0/0
r13	48/19/32	47/20/33	-1/1/1	22/44/34	22/45/33	0/1/-1	21/16/59	22/18/61	-3/1/2
r14	48/20/32	48/21/31	0/1/-1	21/46/33	22/46/32	1/0/-1	23/18/61	21/17/61	0/0/0
r15	50/18/32	46/20/34	-4/2/2	23/45/32	23/46/31	0/1/-1	22/16/61	21/19/59	-2/1/1
r16	47/18/35	50/20/30	3/2/-5	22/43/35	22/46/31	0/3/-4	21/17/61	22/17/61	0/2/-2
r17	46/19/35	48/19/33	2/0/-2	23/43/34	23/44/33	0/1/-1	22/17/62	23/16/62	2/0/-1
r18	48/18/33	47/17/36	-1/-1/3	23/44/32	22/43/35	-1/-1/3	23/16/61	22/16/58	0/0/1
r19	47/20/33	48/18/34	1/-2/1	22/46/33	23/46/31	1/0/-2	23/18/59	25/18/59	2/-2/-1
r20	48/19/32	47/18/35	-1/-1/3	22/46/32	23/43/33	1/-3/1	19/20/57	23/18/62	0/-2/2
r21	44/19/37	45/19/33	1/0/-2	20/42/39	21/44/35	1/2/-4	21/18/63	20/19/60	1/0/-1
r22	47/17/35	47/20/34	0/3/-2	21/45/34	20/44/36	-1/-1/2	23/15/62	20/18/60	-3/4/-2
r23	46/18/35	48/18/34	2/0/-1	21/41/39	22/43/36	1/2/-3	19/16/64	21/16/63	2/0/-1
Mean	48/19/33	48/19/32	0/0/0	22/44/33	23/44/32	1/0/-1	22/17/61	22/17/60	1//0/1
STD	2/1/2	2/1/2	2/2/2	1/2/3	2/2/2	2/2/2	2/1/2	2/1/2	2/2/2

Table 5.6 and 5.7 show the percentage of adjunct and conjunct rotations expressed in FE/AA/IE for each movement in average as well as the difference (Δ) between right and left humerus. The difference between right and left humerus as well as left-handed and right-handed subject was low and not statistically significant (p>0.21). The overall results considering both humerus of all subjects (N=31) indicated that the flexion was composed by 48% FE, 19 % AA and 33% IE, the abduction was composed by 45% AA, 22% FE and 33 % IE and the internal/external rotation was composed by 61% IE, 22% FE and 17% AA.

Table 5.7: the combination of adjuncts and conjuncts rotations for each movement during daily activity for the left handed subjects the difference Δ between right and left humerus.

	Flexion			Abduction			Int/ext Rotation		
Subject	Right FE/AA/IE	Left FE/AA/IE	Δ	Right P/Y/R	Left FE/AA/IE	Δ	Right FE/AA/IE	Left FE/AA/IE	Δ
I1	46/21/33	47/21/32	1/0/-1	21/47/32	24/45/31	3/-2/-1	20/16/64	19/17/64	-1/1/0
I2	47/20/33	48/20/32	1/0/-1	21/46/33	21/48/31	0/2/-2	19/17/64	19/18/63	0/1/-1
I3	48/18/34	44/20/36	-4/2/-2	24/45/31	23/39/38	-1/-6/7	25/16/60	22/16/62	-3/0/2
I4	50/19/31	50/21/30	0/2/-1	23/46/31	21/50/29	-2/4/-2	22/17/61	23/18/59	1/1/-2
I5	48/19/33	49/19/32	1/0/-1	23/45/32	22/45/33	-1/0/1	23/16/61	20/18/61	-3/2/0
I6	45/21/34	48/20/33	3/-1/-1	23/46/31	20/47/33	-3/1/2	21/17/62	19/18/63	-2/1/1
I7	49/21/30	49/21/30	0/0/0	24/46/30	23/47/30	-1/1/0	24/16/60	20/18/62	-4/2/2
I8	48/20/33	50/19/31	2/-1/-2	22/44/34	22/45/33	0/1/-1	22/17/61	22/18/60	0/1/-1
Mean	48/19/33	48/20/32	1/0/-1	22/45/33	22/45/32	-1/0/1	22/17/61	22/18/61	0/0/0
STD	2/1/2	2/1/2	2/1/1	1/2/3	2/2/2	2/3/3	2/1/2	2/1/2	2/1/2

Another aspect, which could be studied in shoulder pathology, is the change of humerus movement due to pain. To highlight this point, we have plotted in Figure 5.4 for all control subjects the distribution of each movement per hour in three ranges of angular velocity: slow (up to 50deg/s), medium (between 50deg/s and 100deg/s) and fast (more than 100deg/s). For comparison, we have performed a long-term recording with right-handed patient suffering from of a rotator cuff tear in the right shoulder.

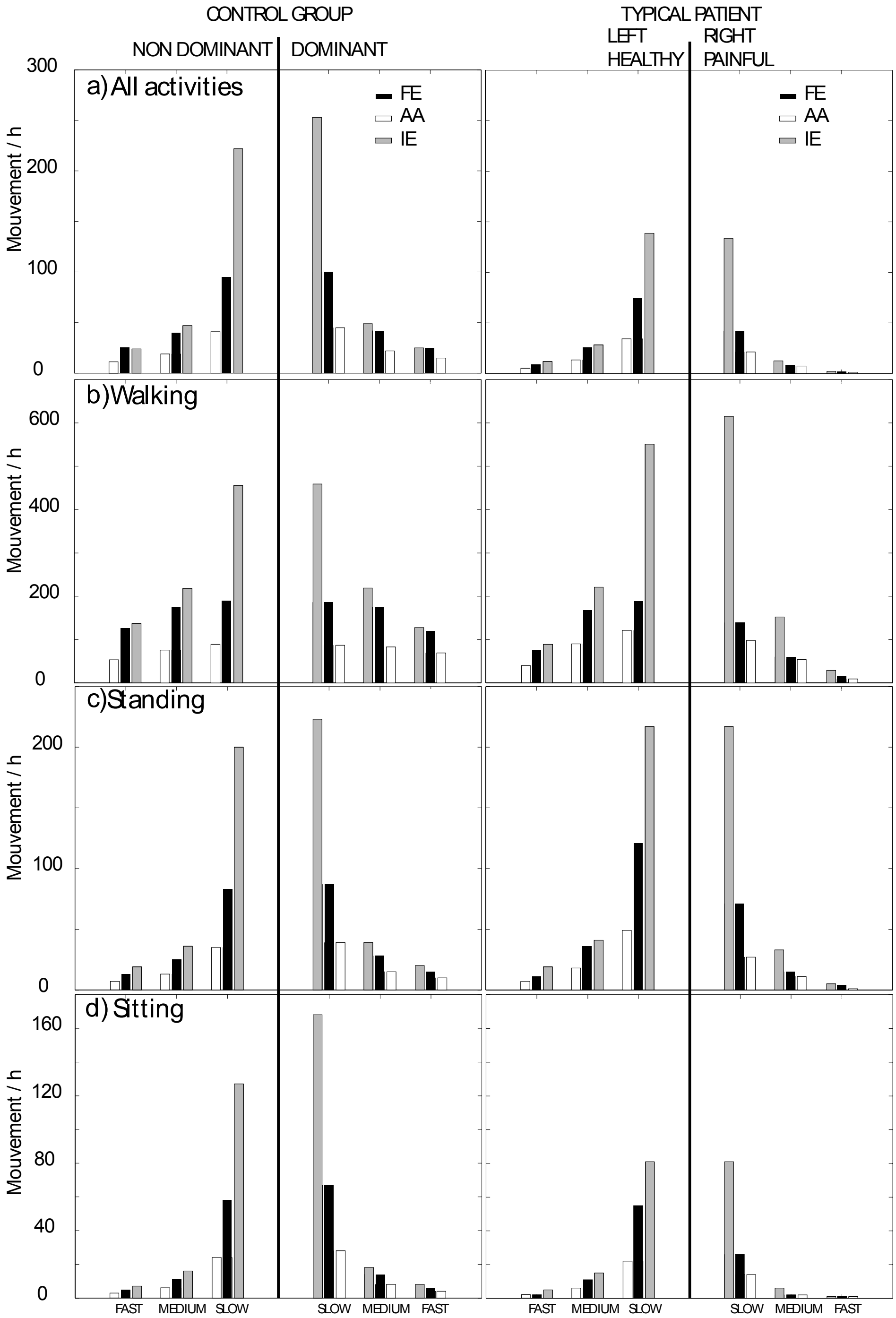

Figure 5.4: Distribution of the movements (Number of movement per hour vs. range of angular velocities values) for the control group and for a typical right-handed patient suffering from rotator cuff disease in the right shoulder a)All activities b)walking. b) standing. c) sitting. Slow (up to 50deg/s), medium (between 50deg/s and 100deg/s) and fast (more than 100deg/s).

The Tables 5.8 and 5.9 show the the distribution of each movement per hour in three ranges of angular velocity for all activities.

Table 5.8: Distribution of the movements per hour for all activities for the right handed subjects

	N_{FE}						N_{AA}						N_{IE}					
	Right			Left			Right			Left			Right			Left		
Subject	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
r1	104	31	21	89	22	12	39	19	17	28	11	9	208	41	22	214	29	9
r2	100	37	12	125	43	11	48	21	7	42	13	5	227	41	10	200	46	16
r3	86	24	19	62	27	17	24	11	9	24	7	5	159	28	16	116	28	20
r4	77	32	17	66	31	15	28	19	13	41	20	10	234	42	17	176	40	14
r5	52	19	15	45	22	25	26	17	11	21	8	11	203	22	15	121	32	23
r6	82	26	13	43	19	9	21	10	6	22	7	3	172	23	12	81	19	9
r7	92	34	9	122	49	16	56	24	8	37	12	6	230	40	9	190	49	18
r8	63	25	11	68	18	9	21	11	6	26	10	3	192	23	12	178	20	12
r9	82	30	18	70	30	19	16	9	11	21	9	6	132	33	15	112	29	19
r10	53	22	11	35	15	17	18	9	12	14	13	6	118	24	13	65	21	13
r11	104	36	21	106	33	13	36	19	10	32	14	10	233	41	19	149	33	18
r12	123	59	31	118	54	25	47	31	18	63	30	15	341	70	28	316	69	22
r13	101	40	17	73	30	19	38	17	13	51	21	14	220	45	24	223	41	22
r14	143	63	39	137	55	28	72	39	29	80	39	19	375	81	37	344	73	30
r15	112	51	44	100	42	31	40	19	22	59	26	17	280	59	45	273	57	31
r16	87	40	25	98	37	35	39	17	20	41	13	11	314	41	29	210	45	39
r17	76	35	22	72	37	28	34	19	13	29	15	9	227	43	24	192	44	31
r18	111	54	38	84	35	26	40	22	19	42	16	9	299	61	41	306	42	24
r19	138	74	36	165	76	40	76	45	30	59	29	14	335	82	42	321	79	41
r20	98	43	41	72	41	35	47	25	20	40	17	14	209	62	47	215	51	38
r21	125	57	30	126	68	36	56	34	22	60	35	19	397	73	25	352	79	38
r22	113	48	33	101	44	29	52	33	19	50	17	13	308	67	33	270	51	27
r23	140	59	34	137	56	29	45	25	16	59	27	11	399	68	28	362	67	22
Mean	98	41	24	92	38	23	40	22	15	41	18	10	253	48	24	217	45	23
Std	26	15	11	34	16	9	16	10	7	17	9	5	81	19	12	88	18	10

Table 5.9: Distribution of the movements per hour for all activities for the left handed subjects

	N_{FE}						N_{AA}						N_{IE}					
	Right			Left			Right			Left			Right			Left		
Subject	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
I1	93	34	28	119	52	34	44	23	18	70	24	18	232	43	30	243	52	32
I2	87	29	15	88	28	15	41	17	13	48	12	4	246	36	17	274	31	14
I3	117	56	32	91	44	27	37	24	21	45	28	17	270	61	38	301	49	22
I4	101	41	22	101	42	23	40	22	18	73	20	13	226	50	2	228	48	27
I5	129	42	25	117	36	15	54	21	14	66	21	8	290	46	26	318	47	16
I6	48	33	26	52	34	19	26	15	14	31	17	11	142	38	26	157	37	20
I7	135	74	32	135	79	49	46	32	19	68	48	24	232	73	34	220	88	45
I8	108	57	34	137	63	40	43	32	24	66	27	14	264	70	28	278	66	38
Mean	102	46	27	105	47	28	41	23	18	58	25	14	238	52	25	252	52	27
Std	28	15	6	28	17	12	8	6	4	15	11	6	45	14	11	52	18	11

Table 5.10: Distribution of the movements per hour for walking periods for the right handed subjects

	N_{FE}						N_{AA}						N_{IE}					
	Right			Left			Right			Left			Right			Left		
Subject	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
r1	175	144	144	126	102	51	51	78	120	78	51	45	436	187	172	638	144	39
r2	181	131	37	257	188	48	110	74	21	86	45	14	497	181	31	439	199	56
r3	153	116	108	217	203	148	103	66	40	48	42	37	460	185	100	386	209	185
r4	157	150	73	169	130	73	42	85	56	126	109	54	446	206	95	442	215	83
r5	120	103	110	128	134	188	100	111	71	56	43	81	547	152	100	424	215	168
r6	202	326	195	209	313	147	72	101	59	156	88	52	410	345	163	476	267	121
r7	163	148	39	233	261	87	128	95	33	64	57	19	533	200	32	456	269	91
r8	160	160	76	114	69	61	76	65	34	76	46	15	400	183	114	552	118	88
r9	265	259	188	208	277	202	73	63	125	75	77	53	443	275	138	429	241	202
r10	146	207	143	151	160	230	89	96	156	99	160	84	420	235	151	375	257	180
r11	210	206	174	267	215	124	92	99	61	79	93	88	409	284	165	370	239	151
r12	168	175	97	164	177	84	59	94	51	130	100	58	505	247	84	504	253	84
r13	226	195	77	149	138	109	80	75	46	117	113	88	475	255	140	481	264	153
r14	176	145	103	210	151	78	111	84	69	118	100	51	462	209	113	502	221	84
r15	171	144	168	164	125	100	67	58	82	112	65	56	429	176	173	436	191	125
r16	171	173	186	186	181	241	58	66	128	67	57	60	388	219	222	381	206	295
r17	192	197	141	200	184	180	92	93	69	71	56	57	428	235	159	416	250	197
r18	151	114	95	110	82	69	49	39	37	55	30	18	475	133	108	500	108	72
r19	219	219	107	246	213	138	86	97	89	107	66	43	465	270	143	470	247	172
r20	179	197	228	165	187	207	63	104	98	79	76	65	355	273	250	381	255	205
r21	181	161	98	167	175	129	82	96	61	75	79	56	503	246	114	495	261	130
r22	120	156	135	122	144	169	96	90	56	65	64	55	466	242	135	445	220	128
r23	181	144	91	214	172	80	62	59	39	79	77	43	569	208	100	580	235	85
Mean	177	173	122	182	173	128	80	82	70	88	74	52	457	224	131	460	221	135
Std	33	50	50	46	59	59	22	18	35	28	30	22	52	48	51	68	45	61

Table 5.11: Distribution of the movements per hour for walking periods for the left handed subjects

	N_{FE}						N_{AA}						N_{IE}					
	Right			Left			Right			Left			Right			Left		
Subject	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
l1	175	146	168	210	197	155	87	73	92	95	79	81	354	186	194	353	210	168
l2	184	146	62	215	117	55	80	61	38	113	58	17	534	160	91	574	138	62
l3	202	191	118	165	164	110	70	84	82	81	108	74	454	238	161	466	222	101
l4	208	238	139	247	257	152	97	134	94	147	97	87	431	307	129	462	252	162
l5	289	152	105	224	131	49	83	70	40	129	79	21	564	189	107	628	197	61
l6	139	129	108	126	147	105	107	52	52	88	66	43	404	170	114	500	177	115
l7	222	212	109	205	201	139	54	74	70	83	76	36	360	244	117	323	240	130
l8	209	210	144	228	209	152	87	121	101	92	69	45	442	293	124	431	223	169
Mean	204	178	119	203	178	115	83	84	71	104	79	51	443	223	130	467	207	121
Std	43	40	32	39	47	43	16	29	25	24	16	27	75	56	33	102	37	44

Table 5.12: Distribution of the movements per hour for standing periods for the right handed subjects.

	N_{FE}						N_{AA}						N_{IE}					
	Right			Left			Right			Left			Right			Left		
Subject	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
r1	105	24	13	94	16	12	32	16	12	25	10	10	175	38	18	191	29	14
r2	95	25	12	101	24	9	45	14	7	38	10	3	211	32	12	186	35	16
r3	95	27	22	77	25	17	31	12	14	28	8	4	195	36	22	145	35	24
r4	65	24	14	56	23	10	20	13	9	29	10	8	195	34	17	180	33	13
r5	50	13	7	45	14	7	21	7	5	16	5	2	175	18	11	123	17	8
r6	84	20	9	57	12	6	11	8	5	21	7	2	185	19	14	99	18	14
r7	77	19	7	110	22	7	56	16	5	39	7	6	220	34	13	191	34	14
r8	56	19	10	65	19	5	16	11	5	17	9	2	147	19	16	134	21	15
r9	86	19	10	73	15	8	15	7	2	19	6	3	129	24	10	108	21	11
r10	31	8	2	23	5	2	6	2	2	7	2	0	87	10	4	44	4	3
r11	113	32	14	117	27	6	32	14	9	24	11	4	242	43	17	178	30	16
r12	116	47	23	100	37	16	49	23	17	55	19	9	303	68	32	303	63	23
r13	101	39	22	75	32	21	32	17	16	57	22	16	239	54	28	253	50	30
r14	106	37	22	99	27	14	54	22	17	57	21	10	296	55	26	265	44	21
r15	84	30	17	70	25	16	31	9	9	48	16	9	221	41	24	224	41	18
r16	86	36	17	90	32	23	45	17	15	45	14	9	314	48	23	206	48	32
r17	67	20	9	64	26	13	29	13	8	26	13	3	225	33	17	189	35	19
r18	82	31	18	62	18	11	33	14	11	33	9	6	205	42	22	214	28	12
r19	112	51	25	139	56	24	65	35	20	46	22	9	291	64	34	284	64	30
r20	89	26	16	60	26	13	53	16	13	34	10	8	182	48	31	202	38	25
r21	101	37	19	102	49	19	45	25	14	49	29	14	345	62	24	313	65	34
r22	106	46	29	106	42	18	45	34	20	45	15	13	318	78	44	299	66	33
r23	116	37	20	107	31	17	37	17	11	50	17	5	330	60	25	299	47	19
Mean	88	29	16	82	26	13	35	16	11	35	13	7	227	42	21	201	38	19
Std	22	11	7	27	12	6	16	8	5	14	7	4	68	18	9	72	17	8

Table 5.13: Distribution of the movements per hour for standing periods for the left handed subjects.

	N_{FE}						N_{AA}						N_{IE}					
	Right			Left			Right			Left			Right			Left		
Subject	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
I1	116	30	22	144	57	33	61	25	15	92	31	17	306	50	31	310	63	35
I2	76	22	15	65	26	17	38	16	13	44	10	4	239	41	14	273	34	12
I3	108	37	18	84	26	14	33	14	10	41	15	7	265	47	26	309	40	19
I4	90	25	13	83	21	14	37	15	12	57	13	7	224	36	14	192	35	23
I5	99	26	13	88	21	10	47	13	9	55	13	5	246	38	20	264	37	16
I6	69	36	20	64	35	21	26	16	15	35	19	13	185	44	31	190	48	21
I7	136	61	21	111	64	36	48	28	10	68	53	27	227	65	27	202	82	43
I8	99	41	22	145	52	28	39	21	14	73	24	10	274	58	27	265	68	29
Mean	99	35	18	98	38	22	41	19	12	58	22	11	246	47	24	251	51	25
Std	22	12	4	32	17	10	11	6	2	19	14	8	37	10	7	50	18	10

Table 5.14: Distribution of the movements per hour for sitting periods for the right handed subjects.

	N_{FE}						N_{AA}						N_{IE}					
	Right			Left			Right			Left			Right			Left		
Subject	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
r1	87	18	8	73	12	5	35	12	4	18	5	2	183	23	5	155	17	6
r2	56	13	2	78	12	1	21	6	2	22	3	2	119	10	5	102	12	5
r3	77	12	8	34	9	4	11	5	3	19	3	1	107	13	9	69	10	4
r4	53	10	5	37	10	5	25	7	4	23	5	2	175	18	7	96	17	6
r5	30	4	0	22	4	1	11	2	0	13	2	1	123	3	2	49	7	3
r6	69	10	4	26	3	2	21	4	2	13	2	1	144	7	4	47	6	3
r7	68	12	2	81	14	4	29	10	4	21	4	2	131	16	5	98	14	7
r8	54	15	5	63	12	6	17	6	4	25	6	2	192	15	5	163	16	8
r9	40	5	1	38	5	3	7	3	1	12	1	1	74	11	6	54	8	4
r10	61	8	1	27	4	3	21	4	0	8	2	1	99	11	2	37	4	1
r11	74	14	5	67	11	3	28	12	3	27	5	2	184	17	5	94	13	5
r12	71	12	5	83	12	6	22	7	2	24	9	2	228	24	7	177	17	8
r13	73	17	5	51	12	3	31	7	5	31	7	1	153	20	11	149	17	4
r14	103	22	11	78	16	8	36	16	9	53	11	5	254	33	14	194	24	14
r15	75	17	8	69	10	8	19	6	5	22	10	5	186	25	13	160	22	11
r16	62	18	6	79	17	12	25	8	7	28	4	3	269	20	11	164	24	13
r17	38	6	2	31	4	4	16	3	1	15	2	1	127	12	3	95	8	6
r18	64	20	6	49	10	4	18	10	6	19	7	2	166	24	13	159	18	7
r19	80	15	8	94	18	4	56	18	6	33	10	3	221	18	12	171	28	10
r20	62	11	6	43	11	4	27	8	3	26	4	2	153	18	9	143	12	10
r21	88	25	6	95	26	12	38	13	10	45	12	2	304	39	13	232	33	19
r22	95	20	10	73	17	6	38	15	7	41	5	3	217	32	17	167	22	10
r23	77	22	10	72	10	8	22	6	2	21	3	1	238	16	8	168	22	5
Mean	68	14	5	59	11	5	25	8	4	24	5	2	176	18	8	128	16	7
Std	18	6	3	23	5	3	11	4	3	11	3	1	59	9	4	54	7	4

Table 5.15: Distribution of the movements per hour for sitting periods for the left handed subjects.

	N_{FE}						N_{AA}						N_{IE}					
	Right			Left			Right			Left			Right			Left		
Subject	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
I1	76	24	14	118	32	22	32	17	9	80	14	9	204	32	19	240	39	19
I2	66	10	5	70	11	4	30	9	8	34	5	2	175	17	7	196	16	8
I3	42	6	4	30	6	2	13	5	4	17	2	0	96	15	6	111	8	4
I4	79	10	4	74	18	9	27	7	3	68	10	4	166	20	8	179	24	9
I5	73	14	8	81	12	4	35	6	6	32	4	4	170	15	8	191	19	6
I6	19	13	11	31	10	3	11	5	5	18	4	3	73	15	12	78	13	5
I7	68	14	7	129	29	16	32	11	4	54	14	9	155	14	15	188	36	17
I8	57	17	7	60	21	12	21	9	7	33	10	4	137	23	8	180	25	12
Mean	60	14	8	74	17	9	25	9	6	42	8	4	147	19	10	170	23	10
Std	20	5	4	36	9	7	9	4	2	23	5	3	43	6	5	51	11	6

5.4 Discussion and conclusion

In this chapter, an ambulatory system was proposed to evaluate the number of movement as well as the rate of adjunct and conjunct rotations of upper limbs during daily physical activity. The method used the velocity of the rotation of the humerus and not the orientation of the humerus, avoiding in this way any noise and drift due to time integration of the gyroscope signals to find angles[5]. The performance of the method to detect the movement and classify adjunct and conjunct rotations lies on the adequate choice of the threshold (th). By using and adaptive threshold we provided a better performance since th was modified based on the amplitude of angular velocity in each windows of one hour. We tested a fixed threshold of 10°/s for the comparison angular velocities for the validation phase but the sensitivity and specificity was low (Table 5.1). We evaluated also the change in th for the phase of validation and for the long term measurement for each subject. We noticed that in average (over 8 hours and all subjects) th was different for the validation phase (th = 52±7 deg/s) where the movement was imposed and the long term measurement (th = 33±3 deg/s) where the movement was natural. To show the efficacy of the adaptive threshold, we calculated the specificity and the sensitivity in the validation phase with a fixed threshold of 33°/s obtained from the long term measurement. The sensitivities and specificities obtained were lower than those with the adaptive threshold (Table 5.1).

Based on 3D inertial sensors on both humerus, our method has quantified the number of flexion, abduction and internal/external rotations between dominant and non-dominant shoulder for a healthy subject for his daily activity (Fig. 5.3). We have shown that dominant shoulder has a higher number of flexions, abductions and internal/external rotations per hour for the sitting, walking and standing posture (Table 5.4 and 5.5). However, based on our population, we have not observed a significant level of difference ($p>0.1$) between the dominant and the non dominant shoulders. These results imply also that the arm predominance does not lie considerably on the number of movements of the arm, but in the intensity of the movement as described rather in chapter 4.

We observed that the number of movements per hour increased from the sitting to the standing posture and from the standing to the walking posture. This was expected since we have more activities during standing and walking compared to sitting. In addition, in daily activities the most common movement was the internal/external rotation and the less frequent one was the abduction. While the movements of flexion were important during the gait for example, the movements of internal/external rotation were performed during all daily tasks like working in an office, cleaning a table etc. This study could be useful to determine daily physical activities which require the most flexion, abduction or internal/external rotations.

Interestingly, despite of the difference on number of movements, the rate of conjunct and adjunct rotations were quite similar for all subjects within each movement (Table 5.6). We can conclude that, for our healthy population, each movement (i.e. flexion, abduction, internal/external rotation) performed during the daily activity was almost “standardized”: for each movement, the three axis of the humerus contributed to the movement at almost fixed rate. We will use these results on patients with pathologies of the shoulder to see if this standardized movement could change due to shoulder pathology in the clinical application (Chapter 7). Actually, a right-handed patient with a painful right shoulder performed more movements with the left shoulder (non-dominant) than the right shoulder (dominant) during his daily activities (Figure 5.4). The movement distribution of the healthy non-dominant shoulder is close to the non-dominant shoulder of control population while the painful shoulder differs not only on the number of movement but also on the velocity distribution. This tendency should be logically reversed after the surgery of the shoulder and recovery. Moreover, we can observe more difference in medium and fast movement than slow movement. What implies that for patients suffering of osteoarthritis or rotator cuff disease, the number of internal/external rotations should be less than the healthy subjects (Figure 5.4) and should increase after surgery (Chapter 7).

A potential extrinsic confounding parameter could be the external charge that can carry the subject during his daily activity with his arm. For example, it is not possible with the proposed method to determine whether a subject is performing ordinary walking or carrying a bag while walking. We can expect that by carrying a bag, the number of flexion will decrease and appears like a disease. Calibrating the ordinary walking of a subject at the beginning of a measurement period or using electromyogram recordings might be a solution. A method which is able to give 3D angles during the daily activity or the intensity of the movement will be complementary to this study. Indeed, the addition of the angles value or the power of the movement with the type of the rotation could illustrate more difference between the left and right shoulder. This study will be also very useful to test prosthetic implants (in laboratory or numerically) because the current load on the shoulder does not correspond to the reality of the use of the shoulder during daily activity[6].

Based on kinematics of the subjects, we were able to find the number of flexions, abductions and internal/external rotations of the humerus during daily activity for a healthy population and to quantify the rate of adjunct and conjunct rotations. This chapter provides preliminary evidence that this system is a useful tool for objectively assessing upper-limb activity during daily activity. The results obtained with the healthy population could be used as control data to evaluate arm movements of patients with shoulder diseases during daily activity (Chapter 7). In the next chapter, a new method to evaluate the level of work was developed in order to supplement the method described in this chapter and in the chapter 4.

5.5 References

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Chapter 6 Working level of the shoulder during daily activity

Abstract - A new method of evaluation for the functional assessment of the shoulder during daily activity is presented. An ambulatory system using inertial sensors attached on the humerus was used to detect the working level of the shoulder. Nine working levels were defined based on the humerus elevation. The method was tested on 31 healthy volunteer subjects. First, we estimated the performance of the system to detect the different working levels of each subject, and then we evaluated their working levels during approximately 8 hours of their daily life. Each working level was recognized with a good sensitivity (range: [80%, 100%]) and specificity (range: [96%, 99%]). During daily activity, we estimated for each detected working level, the frequency (number/per hour) over three different duration, P1 (0s-1s), P2 (1s-5s) and P3 (5s-30s). Our data showed that all subjects had 96% of their working level reached under the 5th level (L5: 100°-120°). No significant difference of the frequency and duration of working levels ($p>0.3$) was observed between dominant and non-dominant side. Our evaluation was made in according to the clinical questionnaire (the Constant score) for the P1 duration, but differed for longer periods P2 and P3. By measuring the working levels and their durations for both shoulders, we proposed a new score to evaluate the ability to work at a specific level. We showed that this score had an average of 100% (±31%) for healthy subjects and can be useful to evaluate the working level in patients with shoulder disease. The proposed technique could be used in many shoulder diseases where problems in performing daily activities should be expressed in terms of objective measures of the upper-limb working level.

6.1 Introduction

The ability to work at a specific level with the shoulder during daily activity is fundamental to better evaluate the pain consequences on joint mobility and the actual functional outcome of the patient. Actually, working with the arms in a elevated position is associated with shoulder disorders[1]. Indeed, in the chapter 5, we described a method to evaluate the movement of flexion-extension, abduction-adduction, and internal/external rotation but we didn't evaluate the working level of these movements. Different questionnaires such as the Constant score[2,3] have assessed the working level. This score consisted of asking the patient if he was able to work with his hand at the pelvis, at the xyphoïd, at the neck, at the head or above the head and increased with the altitude of the level. These assessments are very subjective and thus cannot reflect the actual working level during daily activities. Moreover they cannot give any information about the endurance (frequency and duration) of working at a specific level. Some investigators used pressure sensors[4,5] to develop a system for the objective measurement of the upper-limb activity during person's daily activities. Their system gave three different working levels related to the shoulder without any information about the working level distribution over time. The use of body fixed sensors, such as inertial sensors (e.g. accelerometers and gyroscopes)[6], has proved to be an alternative where the shoulder mobility during daily activity is studied. Hansson et al. evaluated the usability of inclinometry based on tri-axial accelerometers for assessing industrial tasks[7]. They applied the accelerometers on the head, upper back and upper arms. Yet they studied only two different working levels of the upper-arm during short-term measurement.

In this chapter, we used accelerations and angular velocities of the humerus to introduce a new method for long-term recording of the working levels of shoulders during daily activity. The working level is then characterised by the arm elevation, the duration of the stay at specified level and the frequency to reach this level. We described how such an approach can provide a clinical tool to objectively assess the shoulder's function and the outcome of a shoulder pathology treatment.

6.2 Methods

6.2.1 Subjects and materials

Two different studies were conducted. The first study was performed in a laboratory to validate the algorithm quantifying the working level of the humerus. The second was performed in a free living environment to evaluate the validity of the method during daily activities. These studies had received prior ethical approval from the Institutional Ethics Board committee. In both studies, two inertial modules were fixed by a patch on the dorsal side of each distal humerus (Figure 3.1). The inertial module on the humerus measured the anterior elevation-extension (pitch), abduction-adduction (yaw) and internal-external rotation (roll) of the shoulder. The module on the thorax was used to classify daily activities (walking, sitting, standing, lying) using the method proposed by Najafi et al.[8,9] (Chapter 4, 4.2.2 Body posture detection). For this study, working level was estimated only during the periods of walking, standing and sitting.

1) First Study. 5 healthy subjects (26 years old ± 3.8) were enrolled to study the elevation of the humerus segment. While standing, each subject placed his humerus in positions from 0° to 180° by step of 20° in flexion (10 trials) and then in abduction (10 trials). These tests were repeated with each subject to evaluate the repeatability of the system. An Electromagnetic motion capture system (Liberty) was used as reference to evaluate the accuracy and precision of the kinematics data obtained from the inertial sensors. The Liberty system contains a tracker module with electromagnetic coils enclosed in a molded plastic shell that detect the magnetic fields emitted by the source and provided in this way a real-time 3D orientation and the arm position. In order to evaluate the performance of the inertial module for the estimation of the arm inclination, two magnetic Liberty modules (C1 and C2) were fixed by a patch on the dorsal side of the distal humerus, close to the inertial module (Figure 6.1). Two other Liberty modules (C3 and C4) were placed on the wall to get the vertical reference line.

The estimation of the actual angle between the vertical and the humerus was defined as:

$$angle = \mathrm{acos}\frac{\overrightarrow{C1C2}\cdot\overrightarrow{C3C4}}{\left\|\overrightarrow{C1C2}\right\|\left\|\overrightarrow{C3C4}\right\|} \qquad \text{(Equ. 6.1)}$$

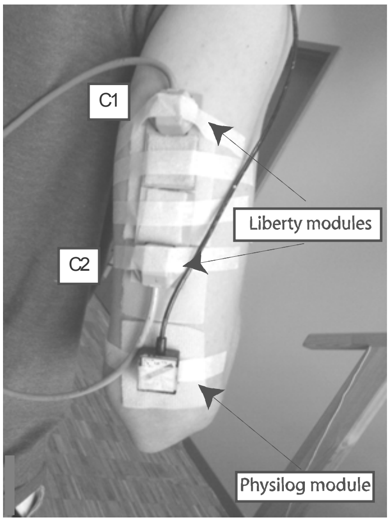

Figure 6.1: Position of the Physilog modules and the Liberty modules (C1 and C2) on the humerus.

2) Second Study: 31 healthy subjects (mean 32 years old ± 8; 18 men, 13 women; 23 right handed, 8 left handed) were studied for long-term measurement. Each subject carried the Physilog system during one day (~8 hours), at home or wherever he/she went. At the end of the recording, the data was transferred to computer for further analysis and to evaluate the level of activity of the subject's shoulder.

6.2.2 Quantification of working levels

We defined a working level as the level during which the arm can be considered as almost motionless. These motionless periods were defined by the following conditions:

- The norm of the accelerations was equal to 1g ± 0.1.
- The norm of the angular velocities was less than 10°/sec.
- The duration was more than 50 ms.

For each motionless period, we used the vertical accelerometers as inclinometers[10,11] and found the mean angle (α) with the vertical. The angle with the vertical is defined as:

$$\alpha = \text{acos}\left(\frac{a_v}{g}\right) \qquad \text{(Equ. 6.2)}$$

where a_v is the vertical acceleration of the humerus and g = 9.81 m/s^2. Based on the value of α, 9 working levels were defined (Figure 6.2) which are an extension of the working level derived from the Constant score with more and precise levels. For each humerus of each subject, we estimated the number of time per hour that the humerus reached each level during the periods of 0 to 1 second (period P1), 1 to 5 seconds (period P2) and 5 to 30 seconds (period P3). These periods were defined in order to take into account the endurance of the activity.

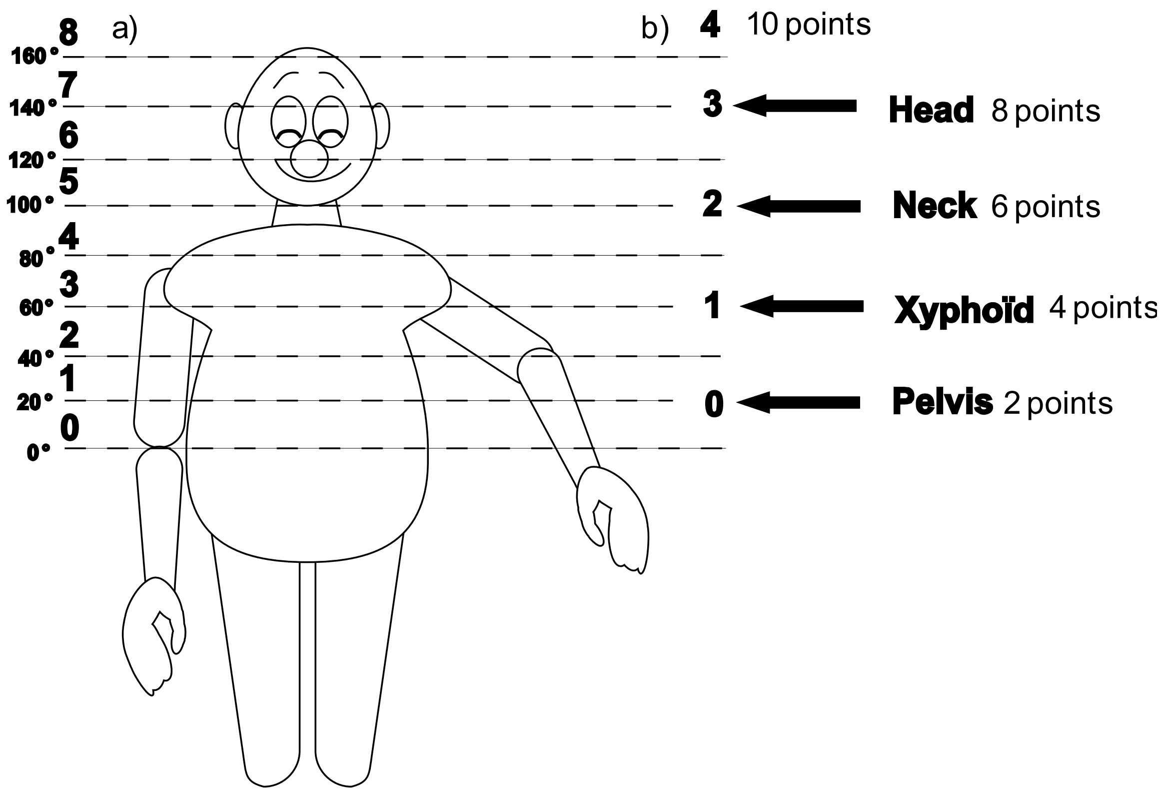

Figure 6.2: Relation between working level of The Constant score (5 working levels) with its weightings b); and the working level of our method (9 working levels) a).

We defined a weighting score (WS) for each level (Li, i=0:8) reached for each period (Pj, j=1:3):

$$WS = \sum_{j=1}^{3} \sum_{i=0}^{8} i \cdot j \cdot Li \qquad \text{(Equ. 6.3)}$$

Where Li = 1 if at least one Li is detected in Pj; Li = 0 otherwise. The coefficient of the working level increased with the level and the duration reached. Therefore, a high score corresponded to a high working level and a long duration. For example, the maximum score (WS=216) will be obtained when a subject reached all the levels during all the periods. A Working Level Score (WLS) was defined in percentage as the ratio of the weighting score for the non dominant shoulder (WS_{ND}) divided by the weighting score for the dominant shoulder (WS_D):

$$WLS = 100 \cdot \frac{WS_{ND}}{WS_D}, \% \qquad \text{(Equ. 6.4)}$$

In the same way, for a patient, the WLS can be defined as the ratio of the weighting score for the painful shoulder (WS_P) divided by the weighting score of the healthy shoulder (WS_H).

6.2.3 Statistical analysis

In order to estimate the performance of the classification of the angles, sensitivity (defined as the ability of the system to correctly identify the true working level) and specificity (defined as the ability of the system to not generate false detection) were estimated. The sensitivity and specificity are calculated as Equation 5.2 and 5.3.

For example, for level L1 the parameters are defined as follow: the true positives were the number of true L1 detections by the system. The false negatives were the number of undetected and misclassified L1. The true negatives were the number of types of levels that are not L1 detected by the method. The false positives were the number of false detections as L1.

In the first study, the error of classification was evaluated by considering the angle obtained by the Liberty system (actual) and the corresponding angle estimated from the inertial sensors (measured):

$$Error_{angle} = (\text{actual angle} - \text{measured angle}) \qquad \text{(Equ. 6.5)}$$

Moreover, to analyze the test-retest reliability results, intra-class correlation (ICC) was used. ICC was defined as a ratio between the true variance and the total variance, where the true variance is the difference between the total variance and the variance due to an error of measurement[12]. ICC is suggested as the measures of the reliability of a single measurement[13].

The Wilcoxon matched pairs signed rank sum test was used as a non-parametric hypothesis test to show whether there were significant differences (at a significance level 5%) between the dominant and the non dominant side.

6.3 Results

A. *First study* :

A total of 200 movements were obtained (40 trials per subjects). Figure 6.3 shows the difference between the angles obtained with the reference system (Liberty) and the angles measured by our method (Bland-Altman Plot)[14]. The mean error (accuracy) was 0.8 degrees and the standard deviation (precision) was 3.8 degrees. Table 6.1 shows the sensitivity and specificity of the 9 working levels detected by the inertial sensors. When considering all 200 movements performed by the enrolled subjects, overall sensitivity and specificity were 90.9% and 98.3% respectively.

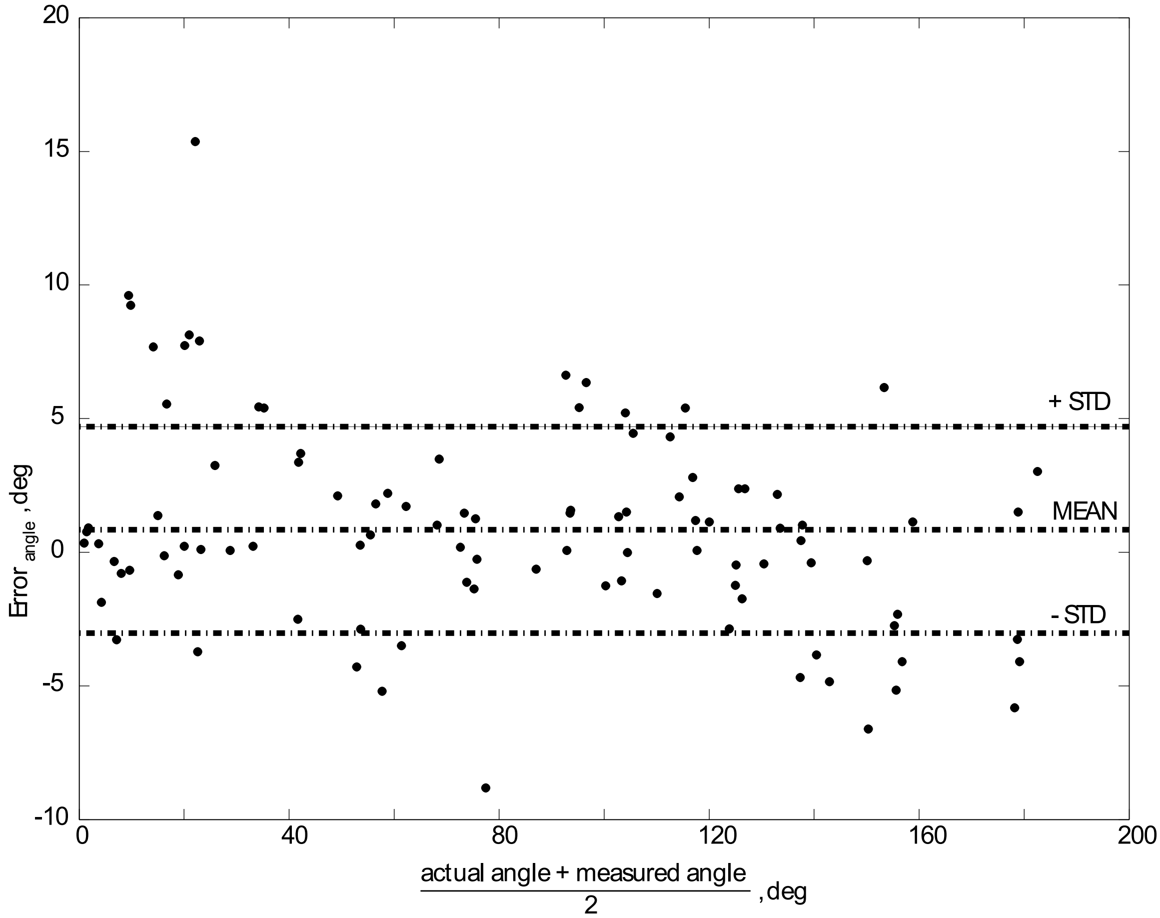

Figure 6.3: Difference between the angles measured by the Liberty system and the angles estimated by our system Physilog.

Table 6.1: Overall sensitivity and specificity of level detection for 5 subjects (200 trials).

Level	TP	TN	FP	FN	Sensitivity,%	Specificity,%
0	30	163	7	0	100.0	96.0
1	17	182	1	0	100.0	99.0
2	19	176	1	4	83.0	99.0
3	19	176	3	2	90.0	98.0
4	14	182	2	2	87.0	99.0
5	25	170	3	2	93.0	98.0
6	23	171	2	4	85.0	98.8
7	16	177	3	4	80.0	98.3
8	12	185	3	0	100.0	98.4
				Mean	90.9	98.3

The ICCs for the Liberty system and the Physilog system were 0.99 and 0.98 respectively. Figure 6.4 shows the results of test-retest obtained for the Physilog system.

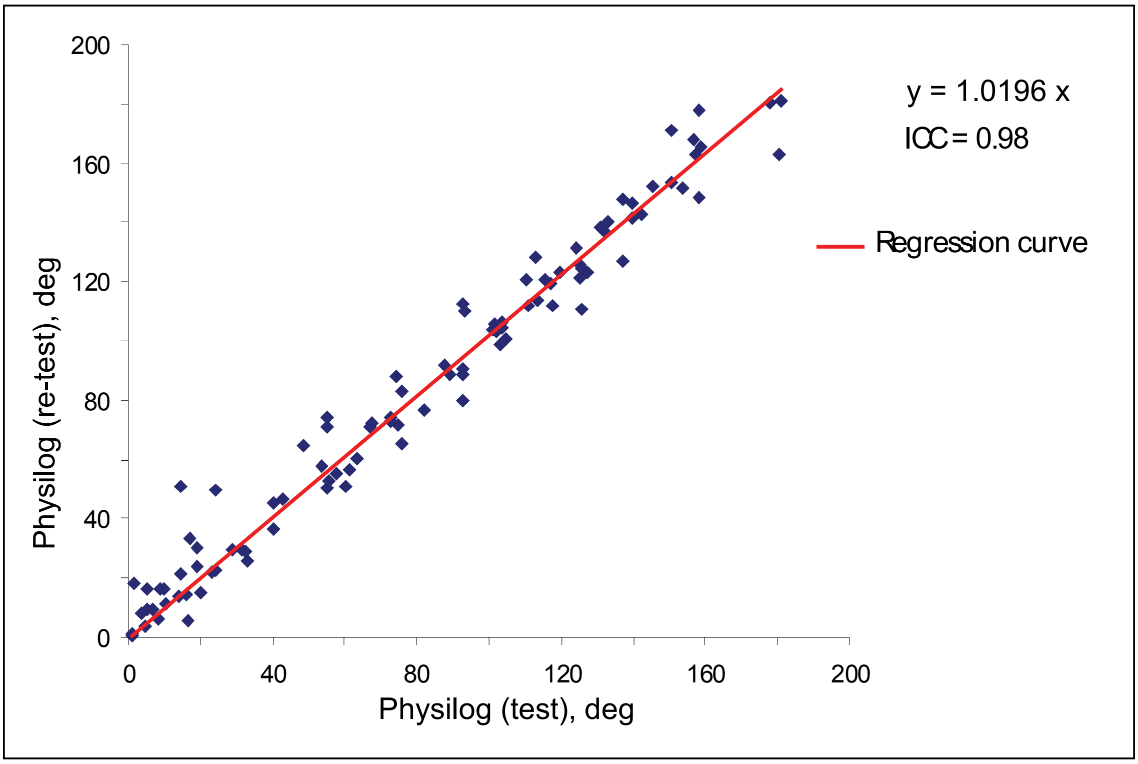

Figure 6.4: Test and re-test results for the estimation of the angles with the Physilog system.

B. Second study :

A total of 209 hours of recording was obtained from all the subjects. Figure 6.5 illustrates the output of the algorithm detecting motionless periods. We can particularly observe that all three criteria are necessary to consider a period as motionless. For each motionless period, the working levels were detected and based on their duration classified into P1, P2 and P3 periods. Considering the Constant score questionnaire, all enrolled subjects were able to work to a level above the head.

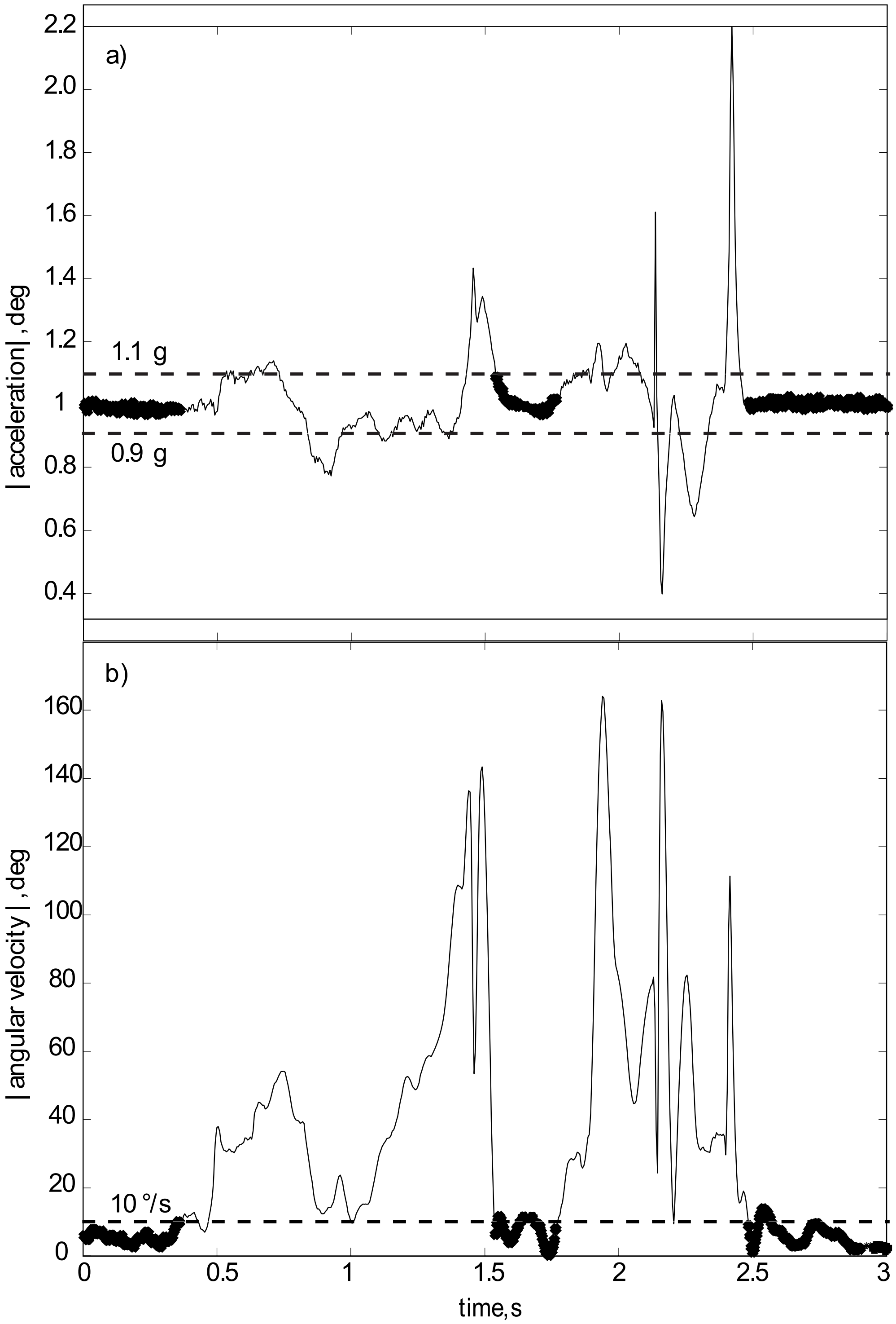

Figure 6.5: Motionless (•) and motion periods for a) the norm of the accelerations and b) the norm of the angular velocities.

Figure 6.6 shows a typical result obtained for a subject during 8 recording hours, where the frequency of each working level (number/hour) was presented for both humerus and all 3 periods P1, P2 and P3. Then, we estimated the frequency of working levels over all subjects by estimating the average of all the data obtained from the 31 healthy subjects.

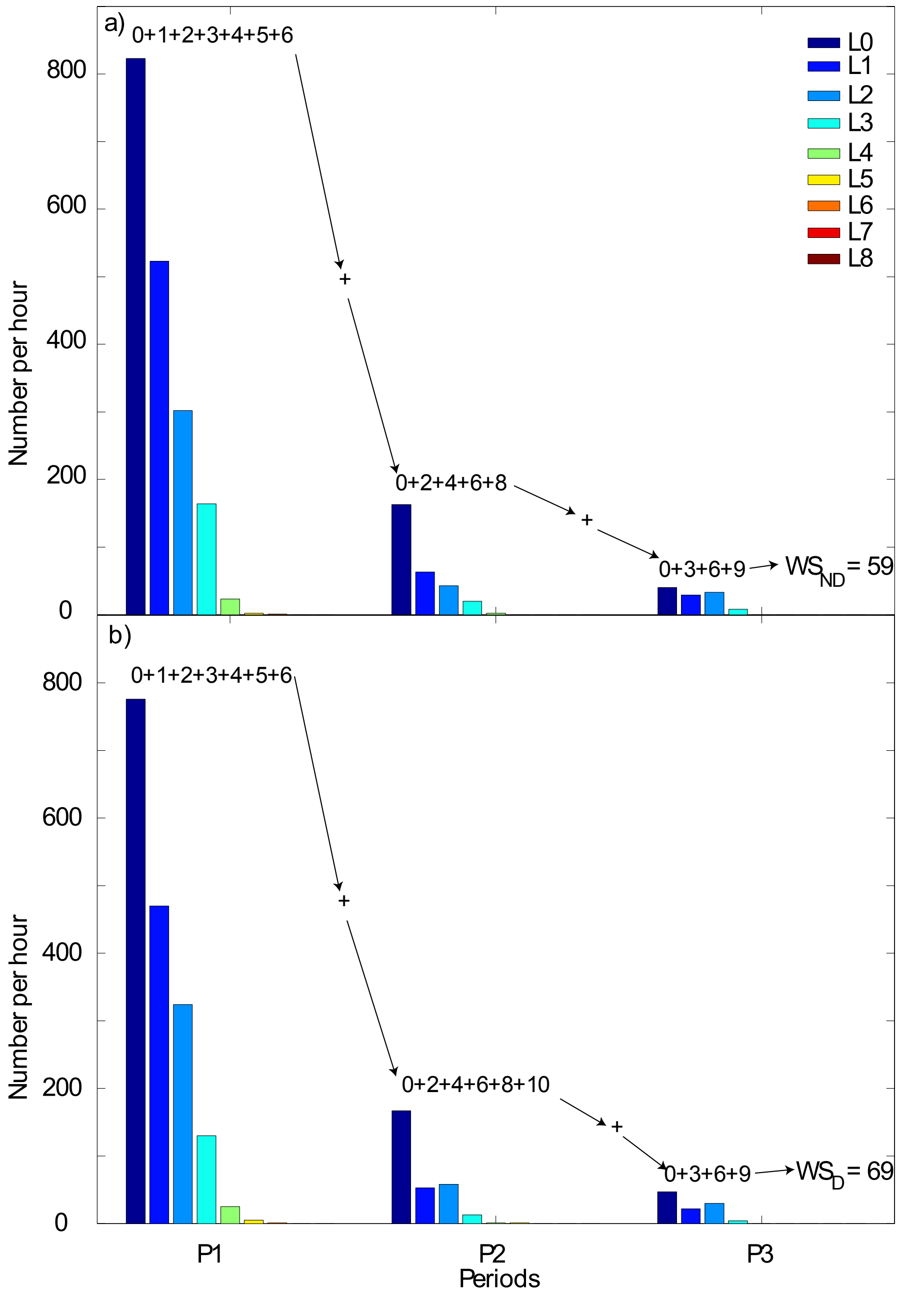

Figure 6.6: Number of level per hour for the periods P1 (0s-1s), P2 (1s-5s) and P3 (5s-30s) for the left humerus a) and the right humerus b) for a typical right handed control subject. WS_{ND}: weighting score for the non dominant shoulder; WS_D: weighting score for the dominant shoulder. Working Level Score (WLS) = $100*WS_{ND}/WS_D$ = 86%.

Table 6.2 summarizes these results where the mean frequency and the standard deviation of working level (L0 to L8 and P1 to P3) are estimated for both the dominant (D) and the non dominant (ND) shoulders. Moreover, the mean of the difference between the dominant and the non-dominant humerus frequency are included for each working level. Comparison between the dominant and the non-dominant humerus was performed for each working level and each period (P1, P2 and P3). No significant difference was observed between the dominant and the non-dominant the frequency and duration of working levels ($p>0.3$), though in average the frequency of the working level is almost higher for the dominant humerus.

Table 6.2: Average of the number per hour for the level reached by all control subjects (209 hours of measurement). D: Dominant shoulder; ND: Non dominant shoulder; Δ : D – ND; std: standard deviation.

	P1						P2						P3					
Levels	D	std	ND	std	Δ	std	D	std	ND	std	Δ	std	D	std	ND	std	Δ	std
L0	928.81	277.02	823.85	282.08	104.97	185.32	170.47	60.90	142.69	53.86	27.78	23.82	53.11	27.33	51.20	24.31	1.91	7.95
L1	513.62	199.75	471.16	189.65	42.46	111.18	56.92	27.85	54.21	26.22	2.72	17.79	16.38	9.16	19.31	12.00	-2.94	10.12
L2	433.03	173.14	332.48	147.29	100.55	143.90	63.69	33.38	50.71	27.29	12.98	22.53	22.48	12.61	23.72	17.36	-1.24	12.65
L3	213.13	135.17	162.10	87.93	51.03	121.71	30.78	25.17	21.07	13.60	9.70	21.73	11.29	12.43	7.89	7.00	3.41	9.92
L4	46.94	45.55	45.79	66.20	1.15	39.93	5.06	5.91	4.82	5.98	0.25	5.04	1.45	2.19	1.39	1.76	0.07	1.43
L5	13.27	25.94	9.91	14.79	3.36	13.60	1.04	1.53	0.79	1.17	0.26	1.13	0.18	0.33	0.27	0.75	-0.09	0.69
L6	2.62	3.02	2.68	2.65	-0.06	2.46	0.12	0.20	0.17	0.25	-0.05	0.28	0.02	0.07	0.02	0.08	0.00	0.11
L7	1.39	2.29	1.60	2.71	-0.21	2.07	0.05	0.15	0.09	0.24	-0.04	0.27	0.01	0.03	0.02	0.11	-0.01	0.11
L8	1.55	4.01	1.04	3.00	0.51	3.48	0.17	0.51	0.16	0.58	0.01	0.61	0.09	0.37	0.04	0.18	0.06	0.41

In order to better evaluate the pertinence of the working level frequency as an evaluation tool, we have reported in Table 6.3 the number of working level per hour reached for a right handed patient suffering of a rotator cuff disease at his right shoulder for the three periods P1, P2 and P3. It can be observed for the right painful side that the patient didn't reach the levels L5 to L8 during the 8 hours of daily activity.

Table 6.3: The number per hour for the level reached by the right handed patient with a rotator cuff disease at his right shoulder. H: healthy shoulder; P: painful shoulder; Δ: P-H.

		P1			P2			P3	
	P	H	Δ	P	H	Δ	P	H	Δ
L0	545.8	572.1	-26.3	111.4	125.8	-14.3	34.3	41.9	-7.6
L1	448.3	295.2	153.1	38.8	28.8	10.0	16.6	12.0	4.6
L2	358.8	292.3	66.4	43.0	36.4	6.6	19.2	12.3	6.9
L3	64.6	150.1	-85.6	8.7	5.7	3.0	3.1	2.0	1.1
L4	34.7	14.9	19.8	2.3	1.7	0.7	0.3	0.1	0.2
L5	0	14.3	-14.3	0	1.2	-1.2	0	0.1	-0.1
L6	0	8.9	-8.9	0	2.6	-2.6	0	1.7	-1.7
L7	0	4.4	-4.4	0	0.6	-0.6	0	0.6	-0.6
L8	0	7.7	-7.7	0	0	0	0	0	0

The Table 6.4 shows the weighting scores for the dominant (WS_D) and the non dominant shoulder (WS_{ND}) as well as the WLS for the 23 right handed and 8 left handed subjects. In average, the WLS for the control subjects is 100% (±31). As a comparison with the same patient, the WS for the healthy (left) and pathologic (right; dominant) shoulder of the patient were respectively 149 and 48 leading to a WLS of 32%.

Table 6.4: Weighting scores for the three periods P1, P2 and P3 and the Working Level Score (WLS) for the 31 healthy subjects. WS_{ND}: weighting score for the non dominant shoulder; WS_D: Weighting score for the dominant shoulder.

	Left humerus	Right humerus	
Right Handed	WS_{ND}	WS_D	*WLS*
r1	45	59	76
r2	59	69	86
r3	65	59	110
r4	65	71	92
r5	45	51	88
r6	96	151	64
r7	81	75	108
r8	78	49	159
r9	198	100	198
r10	36	40	90
r11	53	59	90
r12	59	66	89
r13	65	103	63
r14	88	123	72
r15	88	88	100
r16	79	66	120
r17	59	71	83
r18	96	104	92
r19	71	88	81
r20	79	112	71
r21	69	53	130
r22	58	74	78
r23	53	69	77
Left Handed	WS_D	WS_{ND}	*WLS*
l1	98	76	78
l2	88	66	75
l3	58	58	100
l4	151	126	83
l5	75	103	137
l6	96	123	128
l7	58	66	114
l8	45	71	158
Mean	*76*	*80*	*100*
STD	*32*	*27*	*31*

6.4 Discussion and conclusion

In this study based on 3D inertial sensors on both humerus, an ambulatory system was proposed to quantify the working level of the humerus during daily physical activity of a group of healthy subjects. Compared to the reference electromagnetic system, the results of the first study showed that our method measured the working levels enough accurately. Even with a precision of few degrees, the sensitivity and the specificity of the method were high enough and acceptable (Table 6.1). The reason of the weak sensitivity in some cases (subjects 2, 6 and 7) could come from the fact that some positions of the humerus were at the limit of two different levels (for example: actual angle = 121° = L6; measured angle = 119° = L5).

To estimate the humerus level, we used 3D accelerometers as inclinometers during the motionless periods. Bernmark et al. showed the efficiency of the use of accelerometers as inclinometers to estimate the orientation of the arm in rest position and in slow motion[11]. They showed how the dynamic acceleration influenced the angle of the upper arm in relation to the vertical line and concluded that even in slow arm-swing (<0.40 Hz), the total acceleration was close to 1g. In this study also, to detect the motionless periods, we considered a norm of acceleration around 1g (±0.1). However we have included two other conditions: low angular velocity (<10°/s), corresponding to the quite still period of humerus and a duration of at least 50ms (ten time the sampling periods) to exclude short artifact. The Figure (6.7 a)) shows the duration of all motionless periods for the whole control group. By removing motionless periods that lasted less than 30 seconds, belonging mostly to L0 level and the lying posture, we observed an exponential distribution: the number of short motionless periods was extremely higher than the long duration ones (Figure 6.7 b)). The two decades slop in log-log plot (Figure 6.7 c)) shows that the distribution of the motionless periods follows a power law (non-Poisson statistic)[15]. This power-law distribution appears ubiquitously in the sciences and are empirically observed in a multitude of physical, economic, and engineering systems[16,17,18].

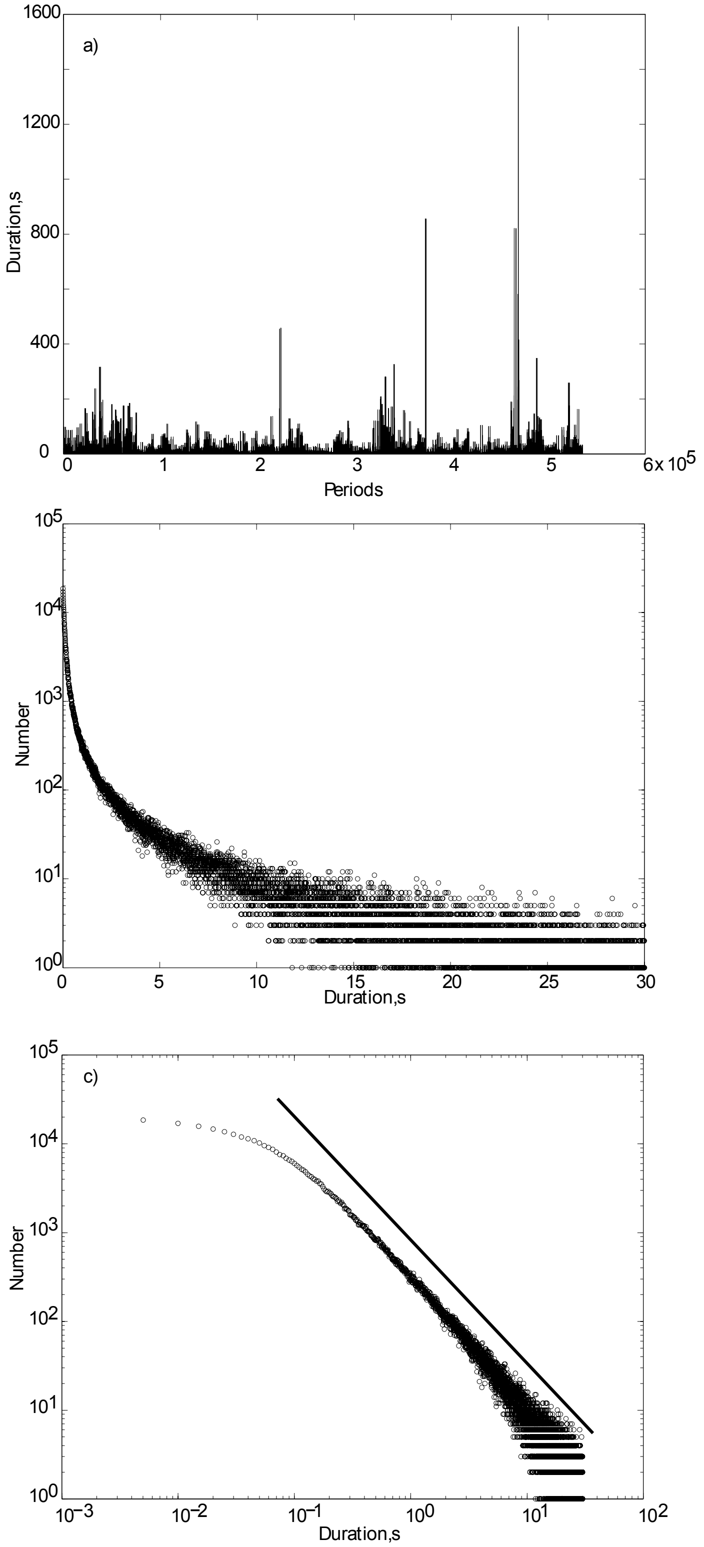

Figure 6.7: a) All motionless periods for all control subjects (209 hours of measurement); b) Distribution of the motionless periods for the period of 50ms to 30 seconds; c) Log-log plot of the distribution, it appears clearly that this distribution is a power-law distribution.

The questions of the Constant score regarding the working level had 5 different levels: pelvis (C0: 0°-45°), xyphoïd (C1: 45°-90°), neck (C2: 90°-120°), head (C3: 120°-150°) and above the head (C4: >150°). The reason we chose 9 levels for our study was that more than 96% of the working levels per hour (Table 6.2) were performed under the "neck" level (L5) and that we wanted to increase the possibility of differentiating the subjects compared the Constant score which offered only 2 levels under the neck. In this study, we showed the difference of working level estimated on actual activity of the subject and that estimated on the basis of the Constant questionnaire. For the short periods (i.e. P1), our evaluation was in accordance to the Constant level where all subjects were assessed to be active at the maximum level of C4 (corresponding to L8, see Figure 6.2). The actual maximum working level for the shoulder during daily activity was in average the L8 (at least once per hour). But for longer periods (i.e. P2 and P3), the frequency of the working level was rarely (in average less than once every six hours, Table 6.2) more than L5 for P2 and more than L4 for P3 (in average less than 1 every 4 hours). This was expected, since it is more difficult to keep the humerus at a high working level during long periods rather than during short periods. The Constant questionnaire didn't give any information of the time spent at a specific level. To include the duration of the working level, we have developed the Working Level Score (WLS). The WLS was calculated with different weights given for each level reached at a specific duration. The higher the humerus and the longer its duration were, the higher was the weight. In the Table 6.4, we can observe the difference of the WLS for the subjects (100% ± 31) and the patient (32%). We can expect that this score will increase after treatment.

Different studies related the problem of working at high level with a shoulder disorder but they used questionnaires to assess this problem[19,20]. In this study, we have proposed an objective method that estimates not only the working level but also the number of times (frequency) that each level was reached. Though, our results showed the frequency of the working levels for the dominant shoulder are in average higher than for the non-dominant side (Table 6.2), statistical tests proved no significant difference between the number per hour of working levels of both shoulders for the healthy subjects. This finding could be exploited in order to evaluate the change of frequency in a painful shoulder. Indeed, we observed that the right handed patient suffering from a rotator cuff disease at his right shoulder didn't reach a level higher than the level L4 for the three periods with his right humerus while the left (non dominant) healthy humerus worked in higher levels. At the same time, it appeared that he had the same frequency distribution on both shoulder for the levels L0 to L4. One should expect that after treatment this patient will work at higher levels with his right shoulder too. However, further results and follow up evaluations after treatment with more patients are needed to confirm these preliminary results (Chapter 7).

Based on humerus kinematics, we were able to estimate for a healthy population, the working level of the shoulder, its duration and its frequency during daily activity. This study provided preliminary evidence on the duration and the frequency distribution of working level and its change between the dominant and the non dominant humerus. The proposed ambulatory system enables the subjects monitoring in their usual environment with minimal interference, in contrast to other systems that require a laboratory setting.

6.5 References

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Chapter 7 Clinical application

Abstract - The clinical application of the algorithms and scores described in the previous chapters is presented. During the short-term measurement (in a hospital), the DASH, SST, ASES and Constant scores (clinical scores), and the P, RAV and M scores (kinematic scores, Chapter 3) were applied to 31 healthy subjects and 26 patients before and after surgery. The kinematics scores showed significant differences ($p<0.02$) between baseline and all follow-ups. Good correlations were found between kinematic and clinical scores, thought the clinical scores showed less sensitivity to change between follow-ups. During the long-term measurement, the algorithm of the estimation of the dominant upper-limb segment, the characterization of the movement of the humerus and the detection of the working level of the shoulder were applied to 10 patients before and after surgery. The measurements at baseline on patients have shown that they have used more their non affected and non dominant side (+14%) during daily activity if the dominant side = affected shoulder. This tendency is reverted after the treatment. If the dominant side ≠ affected shoulder, the patients used much more their dominant side (+24%) compared to the healthy group (+18%). Also, we observed that the patients with a disease at their dominant shoulder performed more movements per hour with their healthy non dominant shoulder. They had less pure internal/external rotations and performed less fast movements. After surgery, these parameters presented no significant differences ($p>0.06$) with the control group. Moreover, the working levels of the painful shoulder were lower than the healthy shoulder before and after surgery. Compared to the control group (100% ± 31), the Working Level Score (WLS) for the patient at baseline (54% ± 17), 3 months (77% ± 18) and 6 months (87% ± 21) were always lower. However, a significant improvement can be shown after surgery. This clinical application shows the effectiveness of the proposed algorithms and parameters to have an objective outcome evaluation of the shoulder before and after surgery by considering the actual activity of the patient during daily conditions.

7.1 Short-term measurement

7.1.1 Introduction

The rapidly rising cost of healthcare with its financial impact on individuals and the national economy, associated with deficiencies in clinical research methods have stimulated the emergence of the concept of outcome research. Variable definitions of outcome have been used previously to assess outcome after the shoulder treatment. Some of these (such as the Constant score, the American Shoulder and Elbow Surgeons score or the Disabilities of the Arm, Shoulder and Hand score) are widely used. However, none has been recognized as a universal outcome tool. Therefore, we have developed a new ambulatory shoulder movement analysis device that can be used easily by any physician at the hospital or in his practice as well as by the patient at home. It allows the measurement of changes in the biomechanics of the shoulder by noting the effects of these changes on clinical findings and day-living patient pain and activities. The goal of the following study was to validate it clinically for adult patients undergoing shoulder surgery for glenohumeral osteoarthritis and rotator cuff disease.

7.1.2 Patients and methods

The present investigation was set up as a monocentric prospective cohort study over an observation period of 12 months. The same blinded assessor obtained historical and subjective data and made all the clinical observations.

- Inclusion criteria: The patients were required to be at least 18 years old, with a rotator cuff disease implying a supraspinatus rupture of at least 1 cm2, as determined by an MRI, or with a glenohumeral osteoarthritis stage II or III according to the radiologic criteria published by Koss et al.[1]. Informed consent to enter into the study was mandatory.
- Exclusion criteria: Patients who had a previous shoulder treatment (surgery or arthroscopy) or an intra-articular injection in the last six months, who had a

controlateral painful shoulder or a malignant disorder were excluded. Other exclusions criteria included a pregnancy or an inability to understand the visual analog scale (VAS).

- Patient selection: The first 26 patients sent to the clinic with a rotator cuff disease (19 patients) or with a glenohumeral osteoarthritis (7 patients) who met the inclusion criteria were selected. Informed consent to enter into the clinical trial was obtained and patients were then operated on by the same surgeon, following his standardized open delto-pectoral surgical approach and technique.
- Controls: 31 healthy young subjects were selected as controls and signed a consent form. They were younger than the patient group in order to be almost sure they didn't get an unrecognized pathologic shoulder.
- Technique for rotator cuff disease + implants used and rehabilitation program.
- Outcome tool: we used the device described in Chapter 3 (cf Figure 3.1).
- All patients and the 31 healthy subjects had a clinical evaluation with the DASH, SST, VAS, ASES and Constant scores. The same evaluation was done at 3, 6 and 12 months after surgery.
- For all patients, we applied the three scores developed in the chapter 3: P Score, RAV Score and M Score.
- In order to show the evolution of each clinical score, comparisons between baseline and 3 months scores, baseline and 6 months scores, and baseline and 12 months scores were made.

7.1.3 Results of the short-term evaluation

7.1.3.1 Clinical scores

Table 7.1 shows the characteristics of the control group.

Table 7.1: Characteristics of the control group.

Subject	BMI	AGE	Dominant side
r1	17.43	35	R
r2	21.46	24	R
r3	19.84	29	R
r4	19.81	28	R
r5	25.43	35	R
r6	27.31	49	R
r7	26.64	34	R
r8	19.23	40	R
r9	22.63	32	R
r10	29.7	35	R
r11	26.53	46	R
r12	23.3	32	R
r13	24.61	38	R
r14	25.91	37	R
r15	20.03	30	R
r16	25.82	31	R
r17	21.47	27	R
r18	19.49	55	R
r19	31.59	37	R
r20	21.45	32	R
r21	21.6	25	R
r22	19.61	47	R
r23	19.71	28	R
l1	22.31	45	L
l2	22.28	28	L
l3	25.34	27	L
l4	25.4	24	L
l5	22.21	27	L
l6	22.31	22	L
l7	23.18	42	L
l8	23.57	40	L

The average BMI was 23 kg/m^2 ± 3 and the average age was 34 years old ± 8.There was 23 right-handed subjects and 8 left-handed subjects. The Table 7.2 shows the clinical scores for the control group.

Table 7.2: Clinical scores for the control group. Vas_s: VAS score for the stiffness; VAS_p: VAS score for the pain; DASH_pt: DASH score in points; ASES_o: ASES score for the operated side; ASES_h: ASES score for the healthy side. Const_R(L): Constant score for the right(left) side;const_b_R(L): Constant score balanced by the right(left) side.

Subject	VAS_s	VAS_p	DASH_pt	ASES_o	ASES_h	SST	const_R	const_L	const_b_R	const_b_L
r1	0	0	30	100	100	12	87.8	86	89.59	87.76
r2	0	0	30	100	100	12	86	85.4	87.76	87.14
r3	0	0	30	100	100	12	84.4	80.4	87.01	82.89
r4	0	0	30	100	100	12	87.8	87.8	89.59	89.59
r5	0	0	30	100	100	12	93.8	86.6	95.71	88.37
r6	0	0	30	100	100	12	93.2	88.2	101.3	95.87
r7	0	0	30	100	100	12	91.6	88.4	93.47	90.2
r8	0	0	30	100	100	12	87.8	82	97.56	91.11
r9	0	0	30	100	100	12	94.2	93.8	96.12	95.71
r10	0	0	30	100	100	12	97.2	88.2	99.18	90
r11	0	0	30	100	100	12	96	91.4	104.35	99.35
r12	1	1	31	100	100	12	96.8	96.4	98.78	98.37
r13	0	0	30	100	100	12	85.4	82.8	94.89	92
r14	0	0	30	100	100	12	95.4	97	97.35	98.98
r15	0	0	30	100	100	12	89	92.2	98.8	102.4
r16	0	0	30	100	64	11	84.4	82.8	93.7	92
r17	0	0	30	100	100	12	89	88	91.75	90.72
r18	0	0	30	100	100	12	91.8	92.2	125.75	126.3
r19	0	0	32	100	100	12	97.2	95.4	99.18	97.34
r20	0	0	33	100	100	12	84.8	84	94.22	93.33
r21	0	0	30	100	100	12	87.8	89	87.8	89
r22	0	0	34	93	100	12	86.6	85.2	108.25	106.5
r23	0	0	33	100	100	12	94.2	95	96.12	96.94
l1	0	0	30	100	100	11	87.4	88.4	109.25	110.5
l2	0	0	30	100	100	12	95.6	98	98.55	101.03
l3	0	0	30	100	100	12	99.4	97.4	102.47	100.41
l4	0	0	30	100	64	12	100.2	96.6	102.24	106.18
l5	0	0	30	100	100	12	99.4	103	102.47	106.18
l6	0	0	30	100	100	12	86.2	83.2	88.86	85.77
l7	0	0	30	100	100	12	92.2	93.8	100.21	101.95
l8	0	0	30	100	100	12	80.8	92.2	82.45	94.08

The Table 7.3 shows the DASH, ASES, SST and Constant scores in percentage (Non Dominant side/Dominant side). All the scores were almost at 100%.

Table 7.3: DASH, Ases, SST and Constant Scores in percentage for the control group.

Subject	DASH,%	ASES,%	SST,%	Const,%
r1	100	100	100	98
r2	100	100	100	99
r3	100	100	100	95
r4	100	100	100	100
r5	100	100	100	92
r6	100	100	100	95
r7	100	100	100	97
r8	100	100	100	93
r9	100	100	100	100
r10	100	100	100	91
r11	100	100	100	95
r12	99	100	100	100
r13	100	100	100	97
r14	100	100	100	102
r15	100	100	100	104
r16	100	64	92	98
r17	100	100	100	99
r18	100	100	100	100
r19	98	100	100	98
r20	98	100	100	99
r21	100	100	100	101
r22	97	100	100	98
r23	98	100	100	101
l1	100	100	92	99
l2	100	100	100	98
l3	100	100	100	102
l4	100	100	100	96
l5	100	100	100	97
l6	100	100	100	104
l7	100	100	100	98
l8	100	100	100	88
Mean	100	99	99	98
STD	1	6	2	4

Table 7.4 shows the characteristics of the patient group.

Table 7.4: Characteristics of the patient group, Ri: Right; Le, Left; C: Rotator cuff disease; A: osteoarthritis.

Patient	BMI	AGE	Painful side	Pathology
1	24.17	63	Ri	C
2	33.08	57	Ri	C
3	27.72	48	Ri	C
4	32.83	68	Le	C
5	28.72	54	Le	C
6	27.43	57	Le	C
7	22.79	63	Le	A
8	30.56	61	Le	A
9	29.02	55	Ri	C
10	36.89	72	Ri	A
11	23.18	61	Le	C
12	24.78	80	Ri	A
13	22.86	68	Ri	C
14	28.31	59	Ri	A
15	28.33	44	Ri	C
16	26.29	65	Ri	C
17	58.44	56	Ri	C
18	32.96	44	Le	C
19	28.08	59	Ri	C
20	22.15	48	Ri	A
21	19.26	83	Le	A
22	26.73	57	Ri	C
23	28.73	58	Ri	C
24	29.41	58	Ri	C
25	24.54	63	Ri	C
26	24.31	55	Ri	C

The average BMI was 29 kg/m^2 ± 7 and the average age was 60 years old ± 9.

The Tables 7.5 to 7.8 show the clinical scores of the patients at baseline, 3, 6 and 12 months after surgery.

Table 7.5: Clinical scores for the patients at baseline. Vas_s: VAS score for the stiffness; VAS_p: VAS score for the pain; DASH_pt: DASH score in points; ASES_o: ASES score for the operated side; ASES_h: ASES score for the healthy side. Const_R(L): Constant score for the right(left) side;const_b_R(L): Constant score balanced by the right(left) side.

Patient	VAS_s	VAS_p	DASH_pt	ASES_o	ASES_h	SST	const_R	const_L	const_b_R	const_b_L
1	9	10	137	43	100	0	33	82.2	39.76	99.04
2	7.5	1.5	91	78.6	43	7	49	81.5	67.12	111.63
3	3	0	47	49.8	100	9	78.8	75	85.65	81.52
4	7	2	74	57.2	100	5	90	47	108.43	56.63
5	3	4	47	71.8	100	6	93	66	103.33	73.33
6	6	3	93	28.4	100	1	76.6	30.6	104.93	41.92
7	6	7	75	50	71.4	5	64.4	35.8	77.59	43.13
8	4	8	70	64.2	71.4	7	68.8	34.2	82.89	41.2
9	7	6	93	21.2	100	1	26.8	92.2	29.78	102.44
10	7	7	99	50.2	100	1	20.4	71.2	29.57	103.19
11	7	8	79	50	100	4	63.3	30.6	76.56	42.15
12	8	10	128	28.8	100	1	75.8	14	109.86	20.29
13	4	4	51	71.4	100	8	74	93	89.16	112.05
14	9	9	132	14.2	85.6	0	2	62.8	2.74	86.03
15	5	5	83	71.6	100	3	20.8	84	22.61	91.3
16	8	8	81	28.4	50	0	12	86.6	17.14	123.71
17	5	4	83	42.8	92.8	6	48.4	73.4	53.78	81.56
18	0	8	59	64.4	92.8	6	52.8	99	57.39	107.61
19	6	7	100	57.2	100	3	48.6	88.6	54	98.44
20	9	9	112	21.4	100	0	18	88.2	19.57	95.87
21	9	7	107	28.4	100	2	11	84.6	17.19	132.19
22	8	7	80	50	92.8	3	64.2	74.6	71.33	82.89
23	5	5	122	35.6	71.4	2	65.4	21	72.67	23.33
24	8	5	55	92.8	50	7	84.2	40.4	93.56	44.89
25	0	0	75	100	50	4	81.6	40	98.31	48.19
26	3	0	54	78.6	100	9	61.4	90.6	68.22	100.67
Mean	6	6	86	52	87	4	53	65	64	79
STD	3	3	26	23	19	3	27	26	32	32

Table 7.6: Clinical scores for the patients at 3 months after surgery. Vas_s: VAS score for the stiffness; VAS_p: VAS score for the pain; DASH_pt: DASH score in points; ASES_o: ASES score for the operated side; ASES_h: ASES score for the healthy side. Const_R(L): Constant score for the right(left) side;const_b_R(L): Constant score balanced by the right(left) side.

Patient	VAS_s	VAS_p	DASH_pt	ASES_o	ASES_h	SST	const_R	const_L	const_b_R	const_b_L
1	9	10	137	43	100	0	51	88.2	61.45	106.27
2	6	4	101	50.2	78.6	3	22	73.8	30.14	101.1
3	1	0	34	85.8	100	11	78.6	88.6	85.43	96.3
4	4	4	49	78.6	100	11	90	67	108.43	80.72
5	5	4	65	71.4	100	2	76.6	49.4	85.11	54.89
6	3	3	80	64.2	100	6	80.4	50	110.14	68.49
7	2	4	74	85.8	93	6	67.2	30	80.96	36.14
8	1	1	69	64.4	64.2	7	56	34	67.47	40.96
9	4	8	115	14.4	100	1	11	80	12.22	88.89
10	4	2	68	85.8	85.6	6	48.8	73.4	70.72	106.38
11	3	3	50	57.2	100	5	75.4	48.3	86.12	56.02
12	3	3	78	57.2	100	3	75.8	30	109.86	43.48
13	2	2	34	78.6	100	10	71	73	85.54	87.95
14	2	4	97	50.2	78.6	2	32	55.2	43.84	75.62
15	7	1	106	57	100	3	36.2	90.2	39.35	98.04
16	6	8	85	50	100	1	19	72	27.14	102.86
17	2	1	39	78.6	78.8	9	54	52	60	57.78
18	1	5	60	57.4	100	5	29	77.4	31.52	84.13
19	3	5	83	57.2	92.8	6	39.6	86.8	44	96.44
20	0	0	67	85.8	100	7	60.4	82.8	65.65	90
21	3	2	74	85.8	100	7	40	81.2	62.5	126.88
22	1	1	45	92.8	100	7	75.2	90.8	83.56	100.89
23	5	7	113	57.2	92.8	1	80.8	24	89.78	26.67
24	7	7	55	71.6	92.8	2	86.8	27	96.44	30
25	2	2	56	71.4	100	9	88.2	55.4	106.27	66.75
26	0	2	46	78.6	100	8	67.2	86.4	74.67	96
Mean	3	4	72	67	95	5	58	64	70	78
STD	2	3	27	18	10	3	23	22	28	27

Table 7.7: Clinical scores for the patients at 6 months after surgery. Vas_s: VAS score for the stiffness; VAS_p: VAS score for the pain; DASH_pt: DASH score in points; ASES_o: ASES score for the operated side; ASES_h: ASES score for the healthy side. Const_R(L): Constant score for the right(left) side;const_b_R(L): Constant score balanced by the right(left) side.

Patient	VAS_s	VAS_p	DASH_pt	ASES_o	ASES_h	SST	const_R	const_L	const_b_R	const_b_L
1	5	5	94	57.2	100	5	41.6	88.2	50.12	106.27
2	4	3	93	64.6	78.6	4	26	59	35.62	80.82
3	1	1	34	85.6	100	11	94.8	98.2	103.04	106.74
4	2	0	32	92.8	100	10	89.4	82	107.71	98.8
5	1	1	38	85.8	100	10	83	75.9	92.22	84.33
6	2	1	81	64.2	92.8	6	72	54.8	98.63	75.07
7	1	3	54	85.8	85.8	9	72.4	59.2	87.23	71.33
8	0	7	59	93	85.8	5	58.8	35	70.84	42.17
9	5	7	110	28.4	78.6	1	19	83.6	21.11	92.89
10	2	1	68	71.4	71.4	6	61	78	88.41	113.04
11	1	1	54	85.8	100	7	76.3	59.6	87.14	68.07
12	2	1	72	57.2	100	3	75.8	12	109.86	17.39
13	0	0	30	100	100	12	85.4	92.8	102.89	111.81
14	3	3	82	64.2	71.4	5	54.4	63.4	74.52	86.85
15	3	2	82	85.8	100	5	48.2	88.2	52.39	95.87
16	5	8	82	71.4	92.8	2	24	71.2	34.29	101.71
17	1	1	33	100	78.6	11	77.2	76.4	85.78	84.89
18	0	1	45	85.8	100	10	72.4	91.6	78.7	99.57
19	6	4	72	35.6	85.6	7	47.2	87.2	52.44	96.89
20	7	8	107	57	92.8	1	26.4	68.2	28.7	74.13
21	1	1	51	85.8	100	11	53.8	67.2	84.06	105
22	0	0	30	100	100	12	78.8	96.8	87.56	107.56
23	6	6	102	57.2	100	3	83.4	40	92.67	44.44
24	3	5	58	64.4	100	6	72.2	49	80.22	54.44
25	1	1	52	71.4	100	8	74.6	60.6	89.88	73.01
26	0	0	33	100	100	12	78.2	91	86.89	101.11
Mean	2	3	63	75	93	7	63	70	76	84
STD	2	3	26	19	10	4	22	21	25	24

Table 7.8: Clinical scores for the patients at 12 months after surgery. Vas_s: VAS score for the stiffness; VAS_p: VAS score for the pain; DASH_pt: DASH score in points; ASES_o: ASES score for the operated side; ASES_h: ASES score for the healthy side. Const_R(L): Constant score for the right(left) side;const_b_R(L): Constant score balanced by the right(left) side.

Patient	VAS_s	VAS_p	DASH_pt	ASES_o	ASES_h	SST	const_R	const_L	const_b_R	const_b_L
1	3	3	82	50	100	6	48.6	88.2	58.55	106.27
2	9	2	88	35.8	85.6	4	25	68	34.25	93.15
3	0	0	31	85.6	100	11	84	88.4	91.3	96.09
4	0	0	30	100	100	12	91.2	81.2	109.88	97.83
5	1	0	34	92.8	100	12	85	81	94.44	90
6	1	1	50	78.6	92.8	10	80.4	71.8	110.14	98.36
7	2	2	41	93	78.6	11	70.8	65.8	85.3	79.28
8	1	1	71	85.8	49.8	8	36.8	46	44.34	55.42
9	8	8	120	28.4	100	1	13	83.8	14.44	93.11
10	0	0	55	93	85.8	9	70.4	77.8	102.03	112.75
11	5	3	66	78.6	100	7	59	83.6	80.82	114.52
12	2	2	57	78.6	100	8	85	29	132.81	45.31
13	0	0	30	100	100	11	83.4	89.8	100.48	108.19
14	1	1	52	71.4	78.6	8	60.6	67.8	83.01	92.88
15	0	0	30	100	72	12	83	88.2	90.22	95.87
16	2	3	57	78.6	100	6	54.8	57	78.29	81.43
17	1	5	31	100	42.8	11	75.8	63.8	84.22	70.89
18	0	0	35	100	100	11	81	88	88.04	95.65
19	6	6	96	21.4	100	4	40.4	96.2	44.89	106.89
20	6	6	111	57.2	92.8	1	28	76.2	30.43	82.83
21	1	1	55	92.8	100	9	51.6	81.6	80.63	127.5
22	0	0	30	100	100	11	83.4	89	92.67	98.89
23	5	4	101	57.2	92.8	2	45.8	65.6	50.89	72.89
24	3	2	42	85.8	85.8	10	99.6	56.6	110.67	62.89
25	2	2	42	71.4	100	12	73.8	74.2	88.92	89.4
26	0	0	30	100	100	12	80.4	89	89.33	98.89
Mean	2	2	56	78	91	8	65	75	80	91
STD	3	2	28	23	15	4	23	16	28	19

Using the Wilcoxon matched unpaired rank sum test to compare the clinical scores of the patients at baseline, 3, 6 and 12 months after surgery, and the clinical scores of the control group, we found significant differences between the control group and the patients at baseline and follow-up for all clinical scores ($p<0.015$).

We used the Wilcoxon matched pairs signed rank sum test to compare the clinical scores at baseline versus 3 months, baseline versus 6 months and baseline versus 12 months after surgery. The DASH, VAS, ASES and the SST presented significant differences between baseline and the follow-up ($p<0.01$). There was no significant difference (p>0.15) for baseline versus 3 months after surgery with the Constant score, the difference appeared only at 6 months (p<0.01). The ASES_h presented logically no significant difference (p>0.08) between baseline and follow-up. Indeed, the ASES_h evaluates the functionality of the healthy side. It should be the same value between the baseline and the follow-up. All clinical scores presented a significant difference between 3 months and 6 months after surgery (p<0.04). The VAS, ASES and Constant score showed no significant difference between (p>0.05) 6 months and 12 months after surgery but the DASH and SST showed a significant difference (p<0.02).

The Table 7.9 shows the DASH, ASES, SST and Constant scores in percentage (painful side/healthy side) for the patients at baseline, 3, 6 and 12 months after surgery. The results for the DASH scores at baseline, 3, 6 and 12 months after surgery were respectively 54% ± 22, 65% ± 22, 72% ± 21 and 78% ± 23. The results for the ASES scores at baseline, 3, 6 and 12 months after surgery were respectively 67% ± 49, 71% ± 20, 81% ± 21 and 92% ± 43. The results for the SST scores at baseline, 3, 6 and 12 months after surgery were respectively 32% ± 25, 44% ± 27, 58% ± 29 and 70% ± 30. The results for the Constant scores at baseline, 3, 6 and 12 months after surgery were respectively 46% ± 24, 57% ± 22, 68% ± 24 and 75% ± 25.

Table 7.9: DASH score, ASES score, SST score and Constant score in percentage at baseline, 3, 6, 12 months after surgery for the 26 patients.

	Baseline				3 months				6 months				12 months			
Patient	Dash,%	ASES,%	SST,%	Const,%	Dash,%	ASES,%	SST,%	Const,%	Dash,%	ASES,%	SST,%	Const,%	Dash,%	ASES,%	SST,%	Const,%
1	11	43	0	40	11	43	0	58	47	57	42	47	57	50	50	55
2	49	83	58	60	41	64	25	30	48	82	33	44	52	42	33	37
3	86	50	75	95	97	86	92	89	97	86	92	97	99	86	92	95
4	63	57	42	52	84	79	92	74	98	93	83	92	100	100	100	89
5	86	72	50	71	71	71	17	64	93	86	83	91	97	93	100	95
6	48	28	8	40	58	64	50	62	58	69	50	76	83	85	83	89
7	63	70	42	56	63	92	50	45	80	100	75	82	91	92	92	93
8	67	90	58	50	68	100	58	61	76	92	42	60	66	72	67	80
9	48	21	8	29	29	14	8	14	33	36	8	23	25	28	8	16
10	43	50	8	29	68	100	50	66	68	100	50	78	79	92	75	90
11	59	50	33	55	84	57	42	65	80	86	58	78	70	79	58	71
12	18	29	8	18	60	57	25	40	65	57	25	16	78	79	67	34
13	83	71	67	80	97	79	83	97	100	100	100	92	100	100	92	93
14	15	17	0	3	44	64	17	58	57	90	42	86	82	91	67	89
15	56	72	25	25	37	57	25	40	57	86	42	55	100	74	100	94
16	58	57	0	14	54	50	8	26	57	77	17	34	78	79	50	96
17	56	46	50	66	93	100	75	96	98	83	92	99	99	94	92	84
18	76	69	50	53	75	57	42	37	88	86	83	79	96	100	92	92
19	42	57	25	55	56	62	50	46	65	42	58	54	45	21	33	42
20	32	21	0	20	69	86	58	73	36	61	8	39	33	62	8	37
21	36	28	17	13	63	86	58	49	83	86	92	80	79	93	75	63
22	58	54	25	86	88	93	58	83	100	100	100	81	100	100	92	94
23	23	50	17	32	31	62	8	30	40	57	25	48	41	62	17	70
24	79	86	58	48	79	77	17	31	77	64	50	68	90	100	83	57
25	63	100	33	49	78	71	75	63	82	71	67	81	90	71	100	99
26	80	79	75	68	87	79	67	78	98	100	100	86	100	100	100	90
Mean	54	67	32	46	65	71	44	57	72	81	58	68	78	92	70	75
STD	22	49	25	24	22	20	27	22	21	21	29	24	23	43	30	24

7.1.3.2 P score, RAV score and M score

Tables 7.10 and 7.11 show all kinematic scores for the control group and the patients at baseline, 3, 6 and 12 months after surgery.

Table 7.10: P score, RAV score and M score for the 31 healthy subjects.

Subject	P score,%	RAV score,%	M score,%
r1	80	88	78
r2	86	93	80
r3	100	99	92
r4	91	93	69
r5	85	84	77
r6	85	81	80
r7	92	94	96
r8	87	92	83
r9	95	95	94
r10	99	96	90
r11	99	97	91
r12	96	98	95
r13	91	91	82
r14	95	96	86
r15	92	94	80
r16	96	92	85
r17	96	96	67
r18	85	96	77
r19	82	85	70
r20	74	84	80
r21	83	87	90
r22	97	95	77
r23	98	88	89
l1	79	84	62
l2	94	99	93
l3	95	97	93
l4	89	93	68
l5	86	98	97
l6	96	100	81
l7	82	84	70
l8	95	99	71
Mean	89.7	92.5	82.0
Std	8.7	5.5	9.8

Table 7.11: P score, RAV score and M score for the 26 patients for baseline and 3,6, and 12 months after surgery.

	RAV score				P score				M score			
Patient	Baseline	3months	6months	12months	Baseline	3months	6months	12months	Baseline	3months	6months	12months
1	42	87	87	69	28	70	76	56	22	64	66	35
2	80	94	93	87	75	74	67	76	51	90	83	61
3	69	79	93	99	57	82	98	90	48	59	97	93
4	70	98	94	90	62	91	93	91	42	37	44	73
5	59	76	76	89	48	59	69	85	25	64	60	99
6	66	76	70	90	48	67	58	81	36	65	52	75
7	5	81	95	93	3	61	97	92	22	63	70	92
8	72	74	95	95	67	64	82	85	55	69	84	87
9	50	62	54	51	36	42	33	29	15	31	23	29
10	50	80	94	98	32	57	84	94	20	76	92	74
11	84	94	97	90	67	88	87	82	55	69	86	95
12	64	60	66	63	38	39	39	44	25	44	42	48
13	70	86	81	90	62	80	77	84	33	50	77	68
14	26	75	88	79	12	64	94	88	6	48	71	98
15	42	63	89	98	32	50	84	98	7	38	73	92
16	48	48	61	90	30	30	45	78	9	7	12	84
17	64	84	86	96	67	76	90	96	44	62	84	96
18	65	55	79	95	50	35	68	92	26	26	57	90
19	53	48	63	54	37	33	45	39	23	9	40	24
20	40	66	57	64	27	57	43	57	23	39	32	32
21	46	61	78	78	36	42	71	72	7	21	88	44
22	51	90	97	98	44	86	96	97	32	73	97	95
23	62	31	37	53	45	16	21	33	37	3	1	18
24	73	76	89	96	63	91	76	93	59	48	65	77
25	73	56	90	96	63	38	74	92	51	29	26	88
26	74	88	92	93	59	67	79	94	76	57	53	84
Mean	58	73	81	84	46	60	71	78	33	48	61	71
Std	18	17	16	15	18	21	22	21	18	23	27	26

A. P Score

The P score for the healthy subjects ranged from 79% to 100% (mean: 89.7% ± 8.7) (Table 7.10).

The Wilcoxon matched pairs signed rank sum test indicated significant differences in the P score between the baseline and 3 months, the baseline and 6 months, and the baseline and 12 months ($p<0.01$). The mean P scores were 46%, 60%, 71% and 78% respectively, at baseline, 3 months, 6 months and 12 months after surgery (Table 7.11). Figure 7.1 a) shows the improvement of the P score after surgery in comparison to the baseline values and the control subjects.

We observed significant differences ($p<0.02$) in the P scores between the patients and the healthy subjects at the baseline, at 3 month and at 6 months, but a no significant difference was found between the patients' P score versus the healthy subjects' P score at 12 month ($p=0.08$). We observed a correlation of 0.72, which reflected a fair to good linear response with the SST score (Figure 7.2 a)). The correlation coefficients with the DASH, ASES and Constant score were respectively 0.69, 0.55 and 0.74 (Table 7.10).

B. RAV score

The RAV score for the healthy subject ranged from 84% to 100% (mean: 92.5% ± 5.5) (Table 7.10).

Significant differences were found in the RAV score between the baseline and 3 months, the baseline and 6 months and the baseline and 12 months ($p<0.01$). The average RAV score was respectively 58%, 73%, 81% and 84% at baseline, 3 months, 6 months and 12 months after surgery (Table 7.11). Figure 7.1 b) shows the improvement of the RAV score after surgery in comparison to the baseline values and the control subjects. The healthy subjects' RAV score was significantly higher ($p<0.01$) than the RAV score at baseline, at 3 months, and 6 months but a non significant difference was also found between the RAV score at 12 months and the RAV score of the healthy subjects (p=0.078). We observed a correlation of 0.66, which reflected a good linear response with the SST score (Figure 7.2 b)). The correlation coefficients with the DASH, ASES and Constant score were respectively 0.62, 0.51 and 0.66 (Table 7.12).

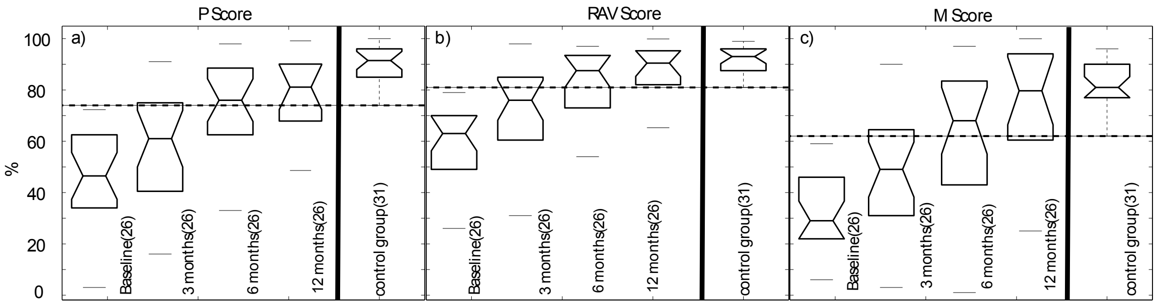

Figure 7.1: Box plot for the P score (a), the RAV score (b) and the M score (c). Boxes contain 50% of the results and the lines represent the range. The dashed line shoes the limit for the healthy subjects.

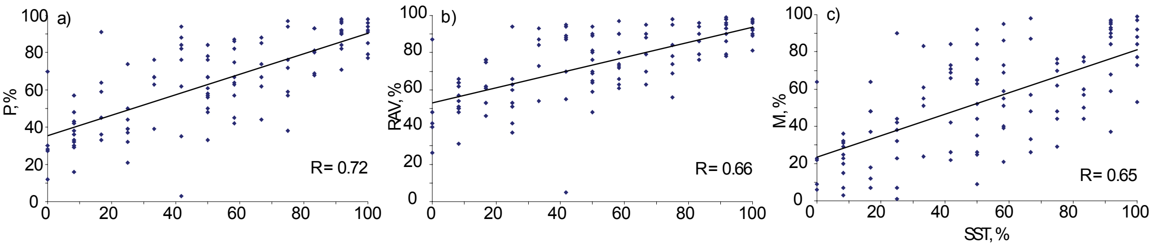

Figure 7.2: Comparison between the SST score and the P score (a), RAV score (b), M score(c).

C. *M score*

The M score for the healthy subjects ranged from 62% to 97% (mean: 82% ± 9.8) (Table 7.10).

The M score at baseline was significantly lower than the M score at 3 months as well as at 6 months and 12 months after surgery (p<0.05). The M score average was respectively 33%, 48%, 61% and 71% at baseline, 3 months, 6 months and 12 months after surgery. Figure 7.1 c) shows the improvement of the M score after surgery in comparison to the baseline values and the control subjects.

We observed significant differences ($p<0.02$) in the M score between the healthy subjects and the patients at baseline, at 3 months and at 6 months, but a no significant difference was found in the M score for the patients at 12 months and the healthy subjects ($p=0.43$). We observed a correlation of 0.65 which reflected a fair to good linear response with the SST score (Figure 7.2 c)). The correlation coefficients with the DASH, ASES and Constant score were respectively 0.6, 0.53 and 0.67 (Table 7.12).

Table 7.12: Coefficient correlation (R) between clinical scores and kinematic scores.

R	SST	Constant	ASES	DASH
RAV score	0.66	0.66	0.51	0.62
P score	0.72	0.74	0.55	0.69
M score	0.65	0.67	0.53	0.6

7.1.4 Discussion and conclusion

While all clinical scores showed a significant difference between the control group and the patient group, and between the baseline and each follow-up, only the DASH and the SST have shown a significant difference between follow-ups.

A remark can be done about the ASES score for the healthy side. We observed that there was no significant difference between the baseline and the follow-up with a $p = 0.076$. This low value of p can be explained by a great standard deviation compared with the other clinical scores.

Our outcome evaluation of shoulder surgery was based on objective scores derived from accurate 3D measurements of shoulder kinematics on healthy and affected individuals performing specific tasks. The RAV score represented the velocity of the humerus. The P score showed how the patient controls the velocity of his humerus using a combination of accelerations and angular velocities. The M score represented the sum of all moments on the shoulder. These scores showed a way to assess the shoulder function based on the quantification of the kinematic differences between the healthy and painful shoulders. Figure 7.1 shows the comparison between baseline, 3, 6 and 12 months after surgery for the three scores. For all the patients, the shoulder mobility increased significantly after surgery. In addition, the scores were clearly distinct between the healthy subjects and the patients with a painful shoulder at baseline without any overlapping of the confidence intervals (Figure 7.1).

Considering that we have a fair to good correlation between our kinematic scores and the clinical scores (Table 7.12), these results suggest that our kinematic scores may be more sensitive to the functional changes of the shoulder than the clinical scores.

The Table 7.9 shows that the patient 9 had poor clinical scores after surgery. He had an inflammatory capsulitis at 6 months after surgery. The kinematic scores (Table 7.11) also detected this post-operative complication with changes that were consistent with the patient suffering with pain while performing some movements. Another complication involved patient 12 who suffered from a chronic dislocation. His clinical scores were improved but the kinematic scores were equal to the baseline, expressing the poor mobility of this patient.

By producing an objective score based on the 3D kinematics of the shoulder, our system assessed the functionality of the shoulder. However, it cannot be used yet to differentiate the type pathologies. Our score is not related directly to pain but to the pain's effect on mobility. This means that in the case where there is no recovery of shoulder functionality even if the pain is removed after surgery, our scores will remain low.

Patients were selected with unilateral symptomatic shoulders. We cannot say that there is no rotator cuff pathology on the so called “good” side, but this is the best reference for the patient we have. This is the reason why, the first comparison for the scores was made intra-patient. However, if the “good” shoulder is asymptomatic, it represents the same concept of reference for all the patients: the goal of function recovery after surgery, taking into account their shoulder joint evolution with their age. Based on this concept, we assumed comparisons across patients.

The correlation between subjective and objective scores (Table 7.12) showed that the P score had the highest correlation with all clinical scores. After more measurements, it should be considered as an argument to be proposed for clinical use.

Based on this study and the limited sample size, it is difficult to decide which score is more adapted. To answer this question we need more subjects and a clinical validation by considering the type of pathology as well as the results of these scores during long-term monitoring of daily activity. Using a α of 0.05, a β of 0.1 and an error of 10% of the mean value of the healthy subjects' kinematic scores, the ideal sample size are 63, 40 and 113 for the P, RAV and M score respectively.

7.2 Long-term measurement

7.2.1 Introduction

We have designed new algorithms for long-term and the measurement of changes in the biomechanics of the patient's shoulder during the daily activity.

The chapter 4 described a new method of estimating the dominant shoulder segment during the daily activity and its intensity based on the P score. The chapter 5 described a method of characterizing the movements per hour of the humerus (flexion-abduction-int/ext rotation) during long-term measurement and estimating the ratio of adjunct and conjunct components. The chapter 6 described a method of estimating the ability to work at a specific level with the humerus during the daily life.

The goal of this chapter was to validate these algorithms clinically for adult patients undergoing shoulder surgery for rotator cuff disease.

7.2.2 Patients and method

The next investigation has been set up as a monocentric prospective cohort study over an observation period of 6 months.

- Inclusion criteria: The patients were required to be at least 18 years old, with a rotator cuff disease implying a supraspinatus rupture of at least 1 cm2, as determined by an MRI. Informed consent to enter into the study was mandatory.
- Exclusion criteria: Patients who had a previous shoulder treatment (surgery or arthroscopy) or an intra-articular injection in the last six months, who had a controlateral painful shoulder or a malignant disorder were excluded. Other exclusions criteria included a pregnancy or an inability to understand the visual analog scale (VAS).
- Patient selection: The first 10 patients (55 years old ± 7) sent to the clinic with a rotator cuff disease who met the inclusion criteria were selected. Informed consent to enter into the clinical trial was obtained and patients were then operated on by the same surgeon, following his standardized open delto-pectoral surgical approach and technique.
- Outcome tool: we used the device described in Chapter 3 (Figure 3.1).
- All patients had a clinical evaluation using the DASH, SST, VAS, ASES and Constant scores. The same evaluation was done at 3 and 6 months after surgery.
- For all patients, we applied the algorithms developed in the chapter 4, 5 and 6.
- Each clinical score was compared between the baseline, 3 and 6 months after surgery.

7.2.2.1 Estimation of the dominant shoulder during the daily activity

We will study the predominant of use of shoulders before and after surgery.

In the chapter 4, the results on the healthy subjects showed that there was a difference of activity between the dominant shoulder and the non dominant shoulder. For this study, we separated the patient group in 2 subgroups: 1) painful non dominant (PND); 2) painful dominant (PD). The PND group is constituted by the patients 1 to 5 (right dominant side, left painful side). The PD group is constituted by the patients 6 to 10 (right dominant side, right painful side and left dominant side, left painful side, see also Table 7.13).

We compared the painful shoulder of the PD group with the healthy dominant shoulder and the painful shoulder of the PND group with the healthy non dominant shoulder at baseline, 3 months and 6 months for each posture (walking, sitting, and standing). We will also compare our score by itself for baseline versus 3 months and baseline versus 6 months for each posture. Our outcome evaluation will be compared to the clinical scores to see a possible correlation.

7.2.2.2 Characterization of the movement of the humerus during the daily activity

We looked at the number of movements done per hour (flexion, abduction and int/ext rotation) during walking, sitting and standing postures, the combination between adjunct and conjunct rotations and the angular velocity distribution of the movement per hour for the patients' healthy and painful shoulder.

In the chapter 5, the results on the healthy subjects for the number of movements during the gait showed that there was not a significant difference of working level between the dominant shoulder and the non dominant shoulder. For the sitting and standing positions, we separated the patient group in 2 subgroups PD and PND. We compared the healthy with the painful shoulder at baseline, 3 months and 6 months for the gait. We compared the results between the PD group and the PND group at baseline and follow-up. We compared also our score between follow-ups and with the clinical scores.

7.2.2.3 Detection of the working level of the humerus during the daily activity

We studied the working levels reached per hour and their duration for the healthy and painful shoulder for the patients.

In the chapter 6, the results on the healthy subjects showed that there was no significant difference of working level between the dominant shoulder and the non dominant shoulder. For this study, we separated the patient group in 2 subgroups: 1) painful shoulders (PS); 2) healthy shoulders (HS). We compared the number of working levels per hour, especially under the level 5 (L5 to L8 = L58) for the PS and the HS at baseline, 3 months and 6 months for each posture, to show the endurance to work above the shoulder (level > L5). We compared our Working Level Score (WLS), which consider the working levels reached during a day and their durations, by itself for baseline versus 3 months, baseline versus 6 months for each posture.

7.2.3 Results

7.2.3.1 Clinical scores

The characteristics and the clinical scores of the control group are presented in Tables 7.1 to 7.3. Table 7.13 shows the characteristic of the ten new patients.

Table 7.13: Characteristics of the patients.

patient	BMI	AGE	Painful side	Dominant side
1	29.41	58	L	R
2	22.86	55	L	R
3	28.74	59	L	R
4	20.83	62	L	R
5	24.54	63	L	R
6	32.93	43	R	R
7	28.34	47	R	R
8	29.41	53	R	R
9	25.96	64	R	R
10	25.82	45	L	L

The average BMI was 27 kg/m^2 ± 4 and the average age was 55 years old ± 8.There was 5 patients with their non dominant shoulder injured and 5 patients with their dominant shoulder injured.

The Tables 7.14 to 7.16 show the clinical scores of the patients at baseline, 3 months and 6 months.

Table 7.14: Clinical scores for the patients at baseline. Vas_s: VAS score for the stiffness; VAS_p: VAS score for the pain; DASH_pt: DASH score in points; ASES_o: ASES score for the operated side; ASES_h: ASES score for the healthy side. Const_R(L): Constant score for the right(left) side;const_b_R(L): Constant score balanced by the right(left) side.

Patient	VAS_s	VAS_p	DASH_pt	ASES_o	ASES_h	SST	const_R	const_L	const_b_R	const_b_L
1	8	5	55	92.8	50	7	84.2	40.4	93.56	44.89
2	4	4	66	64.4	78.6	7	74.6	25	82.89	28.78
3	4	3	65	28.6	85.8	7	72.4	63.4	80.44	70.44
4	5	6	66	42.8	100	6	65.4	44	93.43	62.86
5	0	0	75	100	50	4	81.6	40	98.31	48.19
6	9	7	70	50.4	100	1	10	92.4	10.87	100.43
7	7	8	71	42.8	100	8	70.2	78.8	76.3	85.65
8	7	7	126	0	100	1	6	97	6.67	107.78
9	10	7	96	50	100	3	41	78.2	78.85	150.38
10	7	6	65	64.2	92.8	8	82.4	64.4	103	80.5

Table 7.15: Clinical scores for the patients at 3 months. Vas_s: VAS score for the stiffness; VAS_p: VAS score for the pain; DASH_pt: DASH score in points; ASES_o: ASES score for the operated side; ASES_h: ASES score for the healthy side. Const_R(L): Constant score for the right(left) side;const_b_R(L): Constant score balanced by the right(left) side.

Patient	VAS_s	VAS_p	DASH_pt	ASES_o	ASES_h	SST	const_R	const_L	const_b_R	const_b_L
1	7	7	55	71.6	100	2	86.8	27	96.44	30
2	2	3	65	71.6	64.2	7	71.2	43	79.11	47.78
3	2	3	65	71.4	92.8	11	86.4	59.6	96	66.22
4	2	3	71	64.2	92.8	7	82.8	47	118.29	67.14
5	2	2	56	71.4	100	9	88.2	55.4	106.27	66.75
6	3	3	72	78.8	100	5	43.4	104.6	47.17	113.7
7	4	3	67	64.4	85.6	6	69	76.8	75	83.48
8	3	3	90	43	92.8	4	29	93.2	32.22	103.56
9	7	5	79	57.2	100	3	44.8	88.4	86.15	170
10	2	2	46	85.6	92.8	10	92.6	85.4	115.75	106.75

Table 7.16: Clinical scores for the patients at 6 months. Vas_s: VAS score for the stiffness; VAS_p: VAS score for the pain; DASH_pt: DASH score in points; ASES_o: ASES score for the operated side; ASES_h: ASES score for the healthy side. Const_R(L): Constant score for the right(left) side;const_b_R(L): Constant score balanced by the right(left) side.

Patient	VAS_s	VAS_p	DASH_pt	ASES_o	ASES_h	SST	const_R	const_L	const_b_R	const_b_L
1	3	5	58	64.4	100	6	72.2	49	80.22	54.44
2	2	3	53	64.2	64.2	10	70.4	61.6	78.22	68.44
3	1	1	50	85.8	85.8	12	75.2	61.2	83.56	68
4	1	3	50	64.2	100	9	83.6	59.4	119.43	84.86
5	1	1	52	71.4	100	8	74.6	60.6	89.88	73.01
6	1	1	36	78.6	100	10	74	92.8	80.43	100.87
7	1	3	35	78.6	92.8	12	74.2	78.4	80.65	85.22
8	3	3	98	57.6	100	5	49.2	95.6	54.67	106.22
9	6	4	85	64.2	100	3	61	87	117.31	167.31
10	3	3	40	85.6	85.6	10	82	79	102.5	98.75

Using the Wilcoxon matched unpaired rank sum test to compare the clinical scores of the patients at baseline, 3 and 6 months after surgery, and the clinical scores of the control group, we found significant differences between the control group and the patients at baseline and follow-up for all clinical scores ($p<0.02$) except for the balanced Constant at 3 and 6 months after surgery ($p>0.07$).

We used the Wilcoxon matched pairs signed rank sum test to compare the clinical scores at baseline versus 3 months and baseline versus 6 months. All the clinical scores except the VAS_s (Stiffness) ($p<0.01$) showed no significant differences ($p>0.058$) between baseline and 3 months evaluation but the differences became significant at 6 months evaluation ($p<0.03$).

The Table 7.17 shows the DASH, ASES, SST and Constant scores in percentage for the patients at baseline, 3 and 6 months after surgery. The results for the DASH scores at baseline, 3 and 6 months after surgery were respectively 62% ± 17, 70% ± 10 and 79% ± 17. The results for the ASES scores at baseline, 3 and 6 months after surgery were respectively 66% ± 54, 76% ± 18 and 79% ± 17. The results for the SST scores at baseline, 3 and 6 months after surgery were respectively 43% ± 23, 53% ± 25 and 71% ± 25. The results for the Constant scores at baseline, 3 and 6 months after surgery were respectively 52% ± 29, 70% ± 22 and 78% ± 14.

Table 7.17: DASH score, ASES score, SST score and Constant score in percentage at baseline, 3 and 6 months after surgery for the 10 patients.

	Baseline				3 months				6 months			
Patient	DASH,%	ASES,%	SST,%	Const,%	DASH,%	ASES,%	SST,%	Const,%	DASH,%	ASES,%	SST,%	Const,%
1	79	93	58	48	79	77	17	68	77	64	50	68
2	70	82	58	34	71	112	58	87	81	100	83	87
3	71	33	58	88	71	77	92	81	83	100	100	81
4	70	43	50	67	66	69	58	71	83	64	75	71
5	63	200	33	49	78	71	75	81	82	71	67	81
6	67	50	8	11	65	79	42	41	95	79	83	80
7	66	43	67	89	69	75	50	90	96	85	100	95
8	20	0	8	6	50	46	33	31	43	58	42	51
9	45	50	25	52	59	57	25	51	54	64	25	70
10	71	69	67	78	87	92	83	96	92	100	83	96
Mean	62	66	43	52	70	76	53	70	79	79	71	78
STD	17	54	23	29	10	18	25	22	17	17	25	14

7.2.3.2 Estimation of the dominant shoulder during daily activity

The Table 7.18 shows the results for the estimation of the dominant shoulder during daily activity for the patients at baseline.

Table 7.18: Difference between the dominant and the non dominant side for 10 patients at baseline. PND: non painful dominant shoulder; PD painful dominant shoulder.

		Walk		Sit			Stand		
	Patient	ALSp,%	ARSp,%	ALSp,%	ARSp,%	Activity,%	ALSp,%	ARSp,%	Activity,%
PND	1	35	65	42	58	32	41	59	56
	2	28	72	37	63	70	34	66	88
	3	45	55	35	65	53	34	66	83
	4	39	61	38	62	41	28	72	71
	5	48	52	39	61	68	44	56	71
	Mean	39	61	38	62	53	36	64	74
PD	6	74	26	73	27	39	63	37	66
	7	46	54	34	66	72	43	57	83
	8	52	48	80	20	17	67	33	75
	9	57	43	47	53	41	47	53	85
	Mean	57	43	59	42	42	55	45	77
	10	39	61	43	57	45	46	54	88

We used the Wilcoxon matched pairs unsigned rank sum test to compare all painful shoulders of the PD group with all healthy dominant shoulders and all painful shoulders of the PND group with all healthy non dominant shoulders.

We used the Wilcoxon matched pairs signed rank sum test to compare all painful shoulders of the PD group at baseline with all painful shoulders of the PD group at 3 and 6 months and all painful shoulders of the PND group at baseline with all painful shoulders of the PND group at 3 and 6 months.

At baseline, for the walking, sitting and standing postures, the differences were significant between the PD shoulder and the dominant healthy shoulder ($p<0.04$). On the other hand, we observed a significant difference for the walking and standing posture for the PND shoulders between non dominant shoulders (p<0.05) but we did not find a significant difference for the sitting posture (p>0.8).

The Table 7.19 shows the results for the estimation of the dominant shoulder during daily activity for the patients at 3 months.

Table 7.19: Difference between the dominant and the non dominant side for 10 patients at 3 months after surgery. PND: painful non dominant shoulder; PD painful dominant shoulder.

		Walk		Sit			Stand		
	Patient	ALSp,%	ARSp,%	ALSp,%	ARSp,%	Activity,%	ALSp,%	ARSp,%	Activity,%
PND	1	20	80	41	59	77	24	76	83
	2	25	75	36	64	58	34	66	77
	3	44	56	32	68	62	31	69	79
	4	31	69	36	64	43	23	77	78
	5	48	52	43	57	66	43	57	83
	Mean	34	66	38	62	61	31	69	80
PD	6	63	37	71	29	29	58	42	82
	7	35	65	50	50	44	41	59	65
	8	60	40	62	38	47	59	41	68
	9	56	44	46	54	69	42	58	83
	Mean	54	47	57	43	47	50	50	75
	10	23	77	59	41	45	46	54	80

At 3 months, for the PND group, significant differences appeared between the healthy and painful shoulders for the walking and standing postures (p<0,04) while there was no significant difference for the sitting posture (p>0.8). However, the PD group showed significant differences for all postures (p<0.04).

The Table 7.20 shows the results of the estimation of the dominant shoulder during daily activity for the patients at 6 months.

Table 7.20: Difference between the dominant and the non dominant side for 10 patients at 6 months after surgery. PND: painful non dominant shoulder; PD painful dominant shoulder.

		Walk		Sit			Stand		
	Patient	ALSp,%	ARSp,%	ALSp,%	ARSp,%	Activity,%	ALSp,%	ARSp,%	Activity,%
PND	1	32	68	34	66	37	30	70	72
	2	24	76	42	58	71	41	59	87
	3	35	65	38	62	45	36	64	75
	4	47	53	37	63	49	30	70	79
	5	44	56	36	64	57	45	55	80
	Mean	36	64	37	63	52	36	64	79
PD	6	62	38	47	53	83	56	44	88
	7	51	49	24	76	66	40	60	74
	8	65	35	53	47	51	66	34	72
	9	58	42	43	57	82	42	58	87
	Mean	59	41	42	58	71	51	49	80
	10	40	60	57	43	35	55	45	60

At 6 months after surgery, for the sitting and standing periods, we observed no significant difference for the PND and the PD group ($p>0.052$), but a significant difference ($p<0.02$) arise between the PND shoulders and healthy dominant shoulders for the walk (Table 7.21).

Table 7.21: Summary of the statistical comparison between healthy shoulders and painful shoulders.

	Baseline		3 months		6 months	
Healthy/Painful	PND	PD	PND	PD	PND	PD
Walking	p<0.017	p<0.04	p<0.04	p<0.04	NS	p<0.02
Standing	p<0.05	p<0.005	p<0.02	p<0.02	NS	NS
Sitting	NS	p<0.005	NS	p<0.003	NS	NS

For the difference between the baseline and the follow-up, the difference was not significant between baseline, 3 and 6 months for the PD and PND groups ($0.06<p<0.7$).

The mean of the P parameter during the daily activity for all patients is represented in the Table 7.22.

Table 7.22: Difference of the P parameter between the left and the right shoulder for 10 patients for baseline and 3,6 months after surgery.

		Baseline Mean P		3 Months Mean P		6 Months Mean P	
	Patient	Left shoulder	Right shoulder	Left shoulder	Right shoulder	Left shoulder	Right shoulder
PND	1	43	52	41	56	50	60
	2	54	61	48	61	54	59
	3	41	53	41	56	48	61
	4	40	55	39	52	51	61
	5	52	57	52	57	54	66
	Mean	46	56	44	56	51	61
PD	6	66	48	65	61	57	57
	7	43	50	56	57	46	59
	8	68	57	66	67	53	53
	9	52	54	55	62	50	56
	Mean	57	52	61	62	52	56
	10	52	53	52	61	58	56

At baseline, for the PD and PND groups, we observed significant differences ($p<0.03$) in comparison to the healthy shoulders. At 3 months, the difference became non significant between the PND shoulders and the healthy non dominant shoulders ($p>0.49$), but there was a significant difference between the PD shoulders and the healthy dominant shoulders ($p<0.025$). At 6 months, both groups had no significant difference ($p>0.5$) with the healthy subjects (Table 7.23).

Table 7.23: Summary of the statistical comparison between healthy shoulders and painful shoulders for the P Intensity.

Healthy/Painful	Baseline	3 months	6 months
PD	p<0.03	NS	NS
PND	p<0.03	p<0.025	NS

For the comparison between the baseline and the follow-up, no significant difference was observed between baseline, 3 and 6 months for the PD and PND groups ($p>0.1$).

7.2.3.3 Characterization of the movement of the humerus during daily activity

A. Number of flexions, abductions and int/ext rotations per hour

The Table 7.24 shows the results for the number of flexions-extension (N_{FE}), abductions-adduction (N_{AA}) and int/ext rotations (N_{IE}) per hour for the walking, sitting and standing positions for 10 patients at baseline during daily activity.

For each posture, the results of the chapter 5 showed that there was no significant difference between the dominant and the non dominant humerus for the healthy subjects ($p>0.1$). So, we compared the painful shoulder with the healthy shoulders for the patients.

We used the Wilcoxon matched pairs unsigned rank sum test to compare all painful shoulders of the group with all healthy shoulders. No significant difference ($p>0.06$) appeared between the healthy and the painful shoulder for the sitting posture but for the standing posture, the difference became significant between the painful shoulder and the control group only for the abduction movement ($p<0.03$). Moreover, a significant difference was observed between the healthy and the painful shoulder during the walking activity ($p<0.01$)

The Tables 7.25 and 7.26 show the results for the number of flexions, abductions and int/ext rotations for the walking, sitting and standing positions for 10 patients at 3 and 6 months during daily activity. For the walking activity, we observed a significant difference between the PS group and the control group ($p< 0.02$), but for the sitting and standing postures, no significant difference was observed for the number of movement per hour ($p>0.07$) (Table 7.27). The comparison between the baseline and the follow-up for the PD and PND groups showed no significant difference ($p>0.06$).

Table 7.24: Number of flexions (N_{FE}), abductions (N_{AA}) and int/ext rotations (N_{IE}) per hour during daily activity for10 patients at baseline.

		Walk						Sit						Stand					
		N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}	
	Patient	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left
PND	1	753	451	135	580	847	877	49	41	29	28	122	95	46	33	15	26	170	177
	2	540	350	225	152	801	700	143	97	32	22	273	203	174	127	60	40	370	306
	3	573	504	191	202	825	774	142	98	55	31	265	206	205	139	88	61	353	320
	4	190	199	114	73	731	629	46	35	27	19	132	123	158	90	65	43	307	269
	5	462	527	249	207	885	880	93	107	47	35	226	210	138	155	74	56	350	355
	Mean	504	406	183	243	818	772	95	76	38	27	203	167	144	109	60	45	310	285
	STD	205	134	58	196	57	110	47	35	12	7	72	54	60	48	27	14	81	68
PD	6	215	432	161	251	796	861	29	68	17	30	88	101	90	168	39	73	255	277
	7	234	232	91	96	417	425	158	124	63	58	288	224	112	90	45	41	204	186
	8	299	386	142	83	457	467	15	34	6	13	40	50	57	94	20	38	161	167
	9	374	327	151	168	656	607	77	79	24	34	120	152	194	177	78	83	327	324
	Mean	281	344	136	149	581	590	70	76	27	34	134	132	113	132	46	59	237	239
	STD	72	87	31	78	177	197	65	37	25	19	108	74	58	47	24	23	71	75
	10	345	211	133	141	603	616	65	69	31	30	113	158	149	129	61	52	302	312

Table 7.25: Number of flexions (N_{FE}), abductions (N_{AA}) and int/ext rotations (N_{IE}) per hour during daily activity for10 patients at 3 months.

		Walk						Sit						Stand					
		N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}	
	Patient	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left
PND	1	375	255	88	85	27	460	84	111	55	23	221	189	137	79	61	41	243	201
	2	481	350	189	131	731	661	86	61	26	25	203	151	140	90	60	43	295	274
	3	287	271	226	142	795	732	382	70	62	32	292	190	131	91	84	43	312	289
	4	275	196	168	113	657	632	75	55	44	31	173	166	158	114	77	68	344	302
	5	523	513	290	203	780	832	83	96	49	43	219	213	150	155	78	66	323	325
	Mean	388	317	192	135	598	664	142	79	47	31	222	182	143	106	72	52	303	278
	STD	112	123	74	44	324	137	134	24	14	8	44	24	11	30	11	14	38	47
PD	6	531	544	116	167	959	955	74	123	15	30	115	175	136	118	49	32	203	191
	7	429	434	122	163	664	612	83	68	39	36	181	125	117	115	41	50	232	176
	8	432	442	109	111	656	655	110	109	46	53	236	235	124	125	32	36	283	279
	9	395	424	147	172	691	722	141	128	57	44	274	194	213	196	102	70	356	295
	Mean	447	461	124	153	743	736	102	107	39	41	202	182	148	138	56	47	268	235
	STD	58	56	17	28	145	153	30	27	18	10	69	45	44	39	31	17	67	60
	10	481	448	229	174	854	823	59	78	22	39	144	173	209	235	89	111	416	425

Table 7.26: Number of flexions (N_{FE}), abductions (N_{AA}) and int/ext rotations (N_{IE}) during daily activity for10 patients at 6 months.

		Walk						Sit						Stand					
		N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}		N_{FE}		N_{AA}		N_{IE}	
	Patient	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left	right	left
PND	1	319	286	117	88	382	361	74	69	33	26	110	102	133	106	53	38	181	157
	2	456	374	227	188	847	835	101	100	67	55	240	181	157	151	74	75	358	309
	3	476	308	187	180	767	794	175	97	53	34	189	137	149	124	70	58	322	295
	4	262	359	144	120	726	682	88	54	61	25	208	157	151	84	77	31	305	243
	5	456	443	280	160	753	862	82	65	53	37	219	156	136	134	89	60	295	328
	Mean	394	354	191	147	695	707	104	77	53	35	193	147	145	120	72	52	292	266
	STD	97	61	65	42	181	205	41	20	13	12	50	29	10	26	13	18	67	69
PD	6	329	234	155	245	532	554	186	112	59	110	295	277	150	106	59	109	255	253
	7	345	460	196	193	745	672	123	94	64	37	309	172	134	179	76	63	316	268
	8	185	265	145	177	539	555	65	77	44	70	203	169	72	97	41	71	238	221
	9	349	439	163	152	671	694	149	150	73	54	251	236	196	205	112	82	357	324
	Mean	302	350	165	192	622	619	131	108	60	68	264	214	138	147	72	81	291	266
	STD	79	116	22	39	104	75	51	31	12	31	48	52	51	54	30	20	55	43
	10	410	530	216	165	742	810	56	50	31	36	129	137	84	79	38	47	167	186

Table 7.27: Summary of the statistical comparison between healthy shoulders and painful shoulders for the number of flexions, abductions and int/ext rotations per hour.

Healthy/Painful	Baseline	3 months	6 months
All activities			
Flexion	NS	NS	NS
Abduction	NS	NS	NS
int/ext Rotation	NS	NS	NS
Walk			
Flexion	p<0.003	p<0.02	p<0.008
Abduction	p<0.006	p<0.002	p<0.002
int/ext Rotation	p<0.02	p<0.006	p<0.006
Stand			
Flexion	NS	NS	NS
Abduction	p<0.03	NS	NS
int/ext Rotation	NS	NS	NS
Sit			
Flexion	NS	NS	NS
Abduction	NS	NS	NS
int/ext Rotation	NS	NS	NS

B. Combination of adjunct and conjunct rotation.

The results of the chapter 5 showed that there was no significant difference ($p>0.21$) between the dominant and the non dominant humerus for the healthy subjects. So, we used the Wilcoxon matched pairs unsigned rank sum test to compare all painful shoulders of the PS group with all shoulders from the HS group.The Table 7.28 shows the results for the combination of rotation (FE/AA/IE) for the movement of flexion, abduction and int/ext rotation for 10 patients at baseline during daily activity. For all movements, we observed no significant difference ($p>0.3$) between the healthy and painful shoulders for the AA and FE rotations, but a significant difference appeared for the IE rotation ($p<0.05$).

Table 7.28: The combination of adjuncts and conjuncts rotations for 10 patients at baseline.

		Flexion			Abduction			Rotation		
		Right	Left		Right	Left		Right	Left	
	Patient	FE/AA/IE	FE/AA/IE	Δ	FE/AA/IE	FE/AA/IE	Δ	FE/AA/IE	FE/AA/IE	Δ
PND	1	51/20/29	48/24/28	-3/4/-1	24/46/31	27/43/30	3/-3/-1	22/15/63	20/17/63	-2/2/0
	2	54/17/30	52/17/30	-2/0/0	22/46/32	22/43/34	0/-3/2	22/17/61	20/17/63	-2/0/2
	3	49/17/33	49/19/31	0/2/-2	21/47/32	24/43/32	3/-4/0	23/16/61	22/16/62	-1/0/1
	4	48/19/33	43/18/39	-5/-1/6	22/45/34	21/45/35	-1/0/1	18/17/65	21/16/63	3/-1/-2
	5	46/20/33	48/18/34	2/-2/1	22/44/34	24/46/30	2/2/-4	22/17/61	25/15/60	3/-2/-1
	Mean	50/19/32	48/19/32	-2/1/1	22/46/33	24/44/32	1/-2/0	21/16/62	22/16/62	0/0/0
	STD	3/2/2	3/3/4	3/2/3	1/1/1	2/1/2	2/3/2	2/1/2	2/1/1	3/1/2
PD	6	47/19/33	51/18/31	4/-1/-2	24/42/36	24/46/30	3/4/-6	22/18/60	25/16/59	3/-2/-1
	7	51/19/30	49/20/32	-2/1/2	21/48/30	22/47/30	1/-1/0	23/17/60	22/17/61	-1/0/1
	8	49/18/33	49/19/32	0/1/-1	22/42/37	22/47/31	0/5/-6	20/16/64	24/18/59	4/2/-5
	9	50/18/33	49/19/32	-1/1/-1	24/47/29	22/46/31	-2/-1/2	26/16/58	23/17/60	-3/1/2
	Mean	49/19/32	50/19/32	0/1/-1	22/45/33	23/47/31	1/2/-3	23/17/61	24/17/60	1/0/-1
	STD	2/1/2	1/1/1	3/1/2	1/3/4	1/1/1	2/3/4	3/1/3	1/1/1	3/2/3
	10	47/18/35	46/19/36	-1/1/1	22/43/35	21/42/38	-1/-1/3	25/17/58	20/16/64	-5/-1/6

The Tables 7.29 and 7.30 show the results for the combination of rotations (FE/AA/IE) for the movement of flexion, abduction and int/ext rotation for 10 patients at 3 and 6 months during daily activity. For all movements, no significant difference was observed between the healthy and painful shoulders for the AA, FE and IE rotations ($p>0.09$).

Table 7.29: The combination of adjunct and conjunct rotations for 10 patients at 3 months after surgery.

		Flexion			Abduction			Rotation		
	Patient	Right FE/AA/IE	Left FE/AA/IE	Δ	Right FE/AA/IE	Left FE/AA/IE	Δ	Right FE/AA/IE	Left FE/AA/IE	Δ
PND	1	52/18/30	50/19/31	-2/1/1	21/48/31	22/47/30	1/-1/-1	21/17/62	22/16/61	1/-1/-1
	2	47/20/33	47/19/34	0/-1/1	21/45/34	21/43/35	0/1/1	20/17/64	19/16/64	-1/-1/0
	3	50/18/32	49/20/32	-1/2/0	21/45/34	21/44/36	0/2/2	20/17/63	18/16/66	-2/-1/3
	4	45/19/35	45/20/36	0/1/1	24/40/36	21/45/34	-3/-2/-2	22/16/62	22/15/63	0/-1/1
	5	48/21/31	47/19/33	-1/-2/2	24/47/29	24/46/31	0/2/2	22/17/60	24/16/61	2/-1/1
	Mean	48/19/32	48/19/33	-1/0/1	22/45/33	22/42/36	0/0/0	21/17/62	21/16/63	0/-1/1
	STD	3/1/2	2/1/2	1/2/1	2/3/3	1/6/6	2/3/2	1/0/1	2/0/2	2/0/1
PD	6	50/18/33	51/17/32	1/-1/-1	23/46/31	24/47/29	1/1/-2	23/15/62	24/15/61	1/0/-1
	7	52/18/30	52/18/30	0/0/0	22/47/32	23/49/28	1/2/-4	23/16/60	23/18/60	0/2/0
	8	49/18/33	47/19/34	-2/1/1	22/43/35	23/46/31	1/3/-4	19/17/65	20/17/62	1/0/-3
	9	49/21/30	51/19/30	2/-2/0	22/46/32	23/47/30	1/1/-2	21/19/60	24/18/58	3/-1/-2
	Mean	50/19/32	50/18/32	0/-1/0	22/46/33	23/47/30	1/2/-3	22/17/62	23/17/60	1/0/-2
	STD	1/2/2	2/1/2	2/1/1	1/2/2	1/1/1	0/1/1	2/2/2	2/1/2	1/1/1
	10	45/19/36	48/18/34	3/-1/-2	22/42/36	22/45/32	0/3/-4	22/16/61	23/16/61	1/0/0

Table 7.30: The combination of adjunct and conjunct rotations for 10 patients at 6 months after surgery.

		Flexion			Abduction			Rotation		
	Patient	Right FE/AA/IE	Left FE/AA/IE	Δ	Right FE/AA/IE	Left FE/AA/IE	Δ	Right FE/AA/IE	Left FE/AA/IE	Δ
PND	1	53/20/27	51/20/29	-2/0/2	23/47/30	24/48/28	1/1/-2	23/18/59	25/16/59	2/-2/0
	2	50/19/31	50/20/30	0/1/-1	21/46/33	21/48/31	0/2/-2	20/18/63	21/17/62	1/-1/-1
	3	48/22/30	50/19/31	2/-3/2	24/44/32	21/44/34	-3/0/2	21/17/62	21/16/63	0/-1/0
	4	47/20/33	44/17/39	-3/-3/6	22/46/33	30/40/30	8/-6/-3	20/16/64	25/13/62	5/-3/-2
	5	47/21/32	48/18/34	1/-3/2	21/49/30	22/48/33	0/-2/3	20/18/62	20/18/62	0/0/0
	Mean	49/20/31	49/19/33	0/-2/2	22/46/32	23/45/31	1/-1/0	21/17/62	22/16/62	2/-1/-1
	STD	3/1/2	3/1/4	2/2/3	1/2/2	4/3/1	4/3/3	1/1/2	2/2/2	2/1/1
PD	6	51/19/31	46/22/32	-5/3/1	23/45/32	20/50/30	-3/5/-2	23/17/60	20/20/60	-3/3/0
	7	47/20/33	51/19/31	4/-1/-2	22/46/32	24/46/30	2/0/-2	21/17/62	24/17/59	3/0/-3
	8	49/19/32	48/22/30	-1/3/-2	22/43/35	23/48/30	1/5/-5	19/17/64	21/17/62	2/0/-2
	9	48/21/31	49/18/33	1/-3/2	21/46/33	22/45/33	1/-1/0	20/19/60	24/17/59	4/-2/-1
	Mean	49/20/32	49/20/32	0/1/0	22/45/33	22/47/31	0/2/-2	21/18/62	22/18/60	2/0/-2
	STD	2/1/1	2/2/1	4/3/2	1/1/1	2/2/2	2/3/2	2/1/2	2/2/1	3/2/1
	10	46/20/34	47/21/32	1/1/-2	21/48/31	20/50/30	-1/2/-1	23/16/61	21/17/62	-2/1/1

C. Angular velocity distribution of the flexion, abduction and int/ext rotation

The Table 7.31 shows the summary of the comparison between the healthy and the painful shoulders for all the activities, the walking activity, the sitting and the standing postures.

Table 7.31: Summary of the statistical comparison between the healthy shoulders and painful shoulders for the angular velocity distribution of the number of flexions, abductions and int/ext rotations per hour.

	Baseline			3 months			6 months		
Healthy/Painful	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
All activities									
Flexion	NS	NS	p<0.01	NS	NS	p<0.03	NS	NS	NS
Abduction	NS	NS	p<0.007	NS	NS	p<0.007	NS	NS	NS
int/ext Rotation	NS	NS	p<0.009	NS	NS	p<0.03	NS	NS	NS
Walk									
Flexion	NS	p<0.005	p<0.0009	NS	NS	p<0.0011	NS	NS	p<0.008
Abduction	NS	p<0.0025	p<0.0003	NS	p<0.0055	p<0.0019	NS	p<0.005	p<0.0014
int/ext Rotation	NS	p<0.0006	p<0.0006	NS	p<0.01	p<0.0013	NS	p<0.004	p<0.0018
Stand									
Flexion	NS	NS	p<0.021	NS	NS	NS	NS	NS	NS
Abduction	p<0.04	p<0.02	p<0.007	NS	NS	NS	NS	NS	NS
int/ext Rotation	NS	NS	p<0.024	NS	NS	NS	NS	NS	NS
Sit									
Flexion	NS	NS	NS	NS	NS	NS	NS	NS	NS
Abduction	NS	NS	NS	NS	NS	NS	NS	NS	NS
int/ext Rotation	NS	NS	NS	NS	NS	NS	NS	NS	NS

For all activities, at baseline and 3 months after surgery, we observed a significant difference for the Fast interval (100°/s ->) for all movements. Then, at 6 months after surgery, no significant differences appeared for the three intervals (Slow: 0-50°/s; Medium: 50-100°/s; Fast: 100°/s->).

For the walking activity, at baseline, significant differences between healthy and painful shoulders were observed for the Medium and Fast interval for all movements, but no significant difference was obtained for the Slow interval. At 3 and 6 months after surgery, the flexion movement had a significant different between healthy and painful shoulder only for the third interval. For the abduction and int/ext rotation movement, there were significant differences between healthy and painful shoulders for the Medium and Fast intervals.

For the standing posture, at baseline, significant differences were observed for the three intervals for the abduction and only for the last interval for the flexion and the int/ext rotation. At 3 and 6 months after surgery, no significant difference appeared for the all movements at all intervals.

For the sitting posture, no significant was observed between healthy shoulders and painful shoulders at baseline, 3 and 6 months after surgery.

All results are presented in the Tables 7.32 -7.34 for all activities, in the Tables 7.35-7.37 for the walking activity, in the Tables 7.38-7.40 for the standing posture and in the Tables 7.41-7.43 for the sitting posture.

For the comparison between baseline and the follow-up, the difference was not significant for each posture and each movement.

Table 7.32: Distribution of the movements per hour for the left and right shoulder for 10 patients at baseline for all activities.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	105	66	6	74	38	3	29	16	2	107	17	2	226	46	4	228	40	2
	2	133	34	19	99	22	9	34	13	10	24	10	4	288	34	24	235	25	10
	3	164	83	25	122	63	21	54	33	18	53	24	7	310	89	25	300	56	18
	4	107	51	32	74	37	22	46	27	16	36	16	7	360	59	35	331	37	14
	5	99	56	28	122	55	31	48	28	21	42	22	12	308	54	33	304	51	32
	Mean	122	58	22	98	43	17	42	23	13	52	18	6	298	57	24	280	42	15
	STD	27	18	10	24	16	11	11	9	8	32	6	4	48	20	12	46	12	11
PD	6	42	9	2	74	26	9	21	7	1	34	13	5	133	13	2	139	28	12
	7	132	39	22	112	39	18	46	20	11	50	19	6	271	46	22	259	42	17
	8	32	8	4	48	19	6	10	5	3	17	5	3	83	12	1	78	19	9
	9	108	43	14	100	37	14	38	19	7	49	15	8	207	43	17	208	42	19
	Mean	79	25	11	84	30	12	29	13	6	37	13	6	174	28	11	171	33	14
	STD	49	19	9	29	10	5	16	8	4	16	6	2	83	19	11	79	11	5
	10	74	49	43	81	39	21	27	22	19	39	19	9	197	58	43	265	45	17

Table 7.33: Distribution of the movements per hour for the left and right shoulder for 10 patients at 3 months after surgery for all activities.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	158	58	18	122	30	5	50	24	10	51	10	1	291	48	15	275	24	3
	2	98	27	18	72	20	7	31	14	9	29	10	4	234	27	20	208	21	7
	3	115	45	22	85	35	10	65	33	16	47	14	4	340	54	25	312	33	9
	4	93	55	45	80	37	22	40	30	34	45	24	12	285	86	45	305	50	18
	5	121	63	32	121	63	38	59	34	24	57	24	13	293	69	33	303	67	32
	Mean	117	50	27	96	37	16	49	27	19	46	16	7	289	57	28	281	39	14
	STD	26	14	12	24	16	14	14	8	11	10	7	5	38	22	12	43	19	11
PD	6	113	34	11	126	44	19	23	15	4	29	13	8	193	31	11	199	47	22
	7	100	38	14	99	36	15	33	14	6	47	12	5	225	38	15	172	41	14
	8	108	49	16	111	50	17	50	18	8	62	19	7	215	51	20	203	52	18
	9	135	50	24	134	41	22	49	28	15	48	15	9	273	62	25	229	44	20
	Mean	114	43	16	117	43	18	39	19	8	46	15	7	226	46	17	201	46	18
	STD	15	8	6	16	6	3	13	6	5	14	3	1	34	14	6	24	5	4
	10	70	42	30	82	49	25	25	21	14	40	23	10	195	52	26	212	53	25

Table 7.34: Distribution of the movements per hour for the left and right shoulder for 10 patients at 6 months after surgery for all activities.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	106	36	12	99	28	7	38	17	8	34	10	3	149	38	11	145	28	7
PND	2	105	39	26	112	30	17	57	19	17	58	17	8	288	41	28	252	33	16
PND	3	118	63	24	109	34	14	44	31	15	48	19	7	287	58	22	279	34	12
PND	4	97	48	32	61	32	55	48	25	24	24	11	19	305	59	35	242	44	38
PND	5	87	36	17	80	33	16	57	22	11	42	11	6	243	39	17	228	33	15
PND	Mean																		
PND	STD																		
	6	158	49	23	99	39	23	54	24	17	109	39	17	280	58	30	260	64	39
	7	108	54	27	143	60	24	57	30	18	53	25	9	324	66	31	247	60	28
	8	69	20	5	82	30	10	42	14	6	68	17	7	251	21	6	208	33	18
	9	133	72	36	155	66	43	65	41	26	53	29	19	296	85	42	281	75	44
	Mean																		
	STD																		
PD	10	57	23	13	54	26	13	26	13	8	32	12	7	144	28	11	163	29	11

Table 7.35: Distribution of the movements per hour for the left and right shoulder for 10 patients at baseline for the walking posture.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	395	337	21	253	188	9	67	63	5	497	79	4	614	220	14	666	206	6
PND	2	226	188	126	175	108	67	86	63	76	63	57	32	415	213	173	434	188	78
PND	3	278	238	57	243	205	56	70	78	43	132	61	9	485	286	54	530	200	44
PND	4	98	58	35	82	64	53	57	38	19	40	25	8	589	92	50	506	90	32
PND	5	180	178	103	207	180	140	83	88	78	82	79	46	507	224	153	491	232	158
PND	Mean	235	200	68	192	149	65	73	66	44	163	60	20	522	207	89	525	183	64
PND	STD	111	101	45	69	60	47	12	19	33	190	22	18	81	71	70	86	55	59
	6	139	60	16	188	168	76	98	54	9	121	90	40	615	152	29	551	221	89
	7	143	57	34	133	67	32	49	26	15	59	28	9	305	75	36	327	72	27
	8	154	85	61	186	156	44	49	55	38	42	20	20	316	131	10	277	136	55
	9	204	126	44	192	91	43	76	56	20	99	38	30	451	143	62	418	127	62
	Mean	160	82	39	175	121	49	68	48	21	80	44	25	422	125	34	393	139	58
	STD	30	32	19	28	49	19	24	15	13	36	32	13	145	35	22	120	62	25
PD	10	119	108	119	86	76	49	40	42	51	73	44	24	322	142	139	453	114	49

Table 7.36: Distribution of the movements per hour for the left and right shoulder for 10 patients at 3 months after surgery for the walking posture.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	230	120	25	182	66	7	50	28	11	74	10	1	364	101	23	387	66	7
PND	2	200	153	128	189	120	40	69	67	53	69	47	15	390	179	162	466	129	66
PND	3	136	99	51	157	90	24	110	79	37	89	44	10	604	132	60	607	98	28
PND	4	90	87	98	75	71	51	38	42	88	39	46	28	396	163	98	447	139	46
PND	5	214	196	113	182	195	136	114	96	80	94	74	35	424	229	127	484	231	118
PND	Mean	174	131	83	157	108	52	76	62	54	73	44	18	436	161	94	478	133	53
PND	STD	59	44	43	47	53	50	35	28	32	22	23	14	97	48	55	81	62	42
PD	6	230	197	47	283	184	77	39	64	13	107	39	21	689	210	60	689	184	81
PD	7	218	154	58	241	147	45	62	33	27	105	44	14	442	159	63	413	158	41
PD	8	285	195	45	282	186	74	34	62	12	105	38	22	687	211	63	688	185	76
PD	9	203	139	121	213	215	107	74	77	42	89	72	44	459	226	143	477	254	115
PD	Mean	234	171	68	255	183	76	52	59	24	102	48	25	569	202	82	567	195	78
PD	STD	36	29	36	34	28	25	19	19	14	8	16	13	137	29	41	143	41	30
PD	10	148	158	174	150	193	105	73	87	69	65	77	32	420	258	176	491	225	107

Table 7.37: Distribution of the movements per hour for the left and right shoulder for 10 patients at 6 months after surgery for the walking posture.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	195	96	28	173	90	23	70	36	12	57	28	3	230	122	30	235	102	23
PND	2	185	140	131	220	84	70	100	54	73	100	58	30	519	170	158	610	161	64
PND	3	182	211	83	183	85	40	53	81	53	108	53	19	504	193	70	654	103	38
PND	4	141	93	58	85	70	207	60	45	55	29	26	69	567	134	69	426	124	154
PND	5	192	166	98	171	166	106	125	96	59	85	46	29	433	213	106	560	191	111
PND	Mean	179	141	80	166	99	89	82	62	50	76	42	30	451	166	87	497	136	78
PND	STD	22	50	39	50	38	73	30	25	23	33	15	24	132	38	48	170	39	54
PD	6	182	98	48	112	80	41	66	55	34	121	86	38	345	122	65	323	153	78
PD	7	157	119	69	236	157	67	83	65	48	97	73	23	484	175	86	418	174	80
PD	8	121	50	15	134	96	35	79	40	25	103	54	20	442	72	25	383	105	68
PD	9	155	115	79	228	125	86	65	62	36	64	51	37	388	180	103	416	171	107
PD	Mean	154	96	53	178	115	57	73	56	36	96	66	30	415	137	70	385	151	83
PD	STD	25	32	28	64	34	24	9	11	9	24	17	9	61	51	34	44	32	17
PD	10	174	133	103	206	216	108	108	61	47	71	74	20	508	162	71	550	179	81

Table 7.38: Distribution of the movements per hour for the left and right shoulder for 10 patients at baseline for the standing posture.

	Patient	N_{FE} Right Slow	Medium	Fast	Left Slow	Medium	Fast	N_{AA} Right Slow	Medium	Fast	Left Slow	Medium	Fast	N_{IE} Right Slow	Medium	Fast	Left Slow	Medium	Fast
PND	1	35	10	1	27	5	1	11	4	1	21	4	1	149	18	3	162	14	2
	2	122	31	21	97	22	9	37	13	10	25	11	4	299	43	28	261	30	14
	3	134	51	20	95	32	12	52	24	12	37	17	7	268	61	24	267	36	16
	4	91	40	27	58	23	9	33	19	13	27	10	6	221	51	35	223	31	14
	5	84	37	17	101	39	15	41	20	13	35	13	8	276	46	27	284	48	24
	Mean	93	34	17	76	24	9	35	16	10	29	11	5	243	44	23	239	32	14
	STD	39	15	10	32	13	5	15	8	5	7	5	3	60	16	12	49	12	8
PD	6	71	15	4	121	36	11	27	11	1	49	18	7	217	33	5	217	41	19
	7	79	19	13	65	17	8	27	11	7	27	10	3	164	28	12	150	24	12
	8	49	6	1	63	23	9	14	4	1	24	10	4	146	12	3	130	21	15
	9	133	46	15	117	44	15	48	22	7	56	18	8	246	56	25	242	56	26
	Mean	83	22	8	92	30	11	29	12	4	39	14	6	193	32	11	185	36	18
	STD	36	17	7	32	12	3	14	7	3	16	5	2	46	18	10	53	16	6
	10	70	46	33	75	36	18	25	22	14	29	16	7	199	65	38	236	55	21

Table 7.39: Distribution of the movements per hour for the left and right shoulder for 10 patients at 3 months after surgery for the standing posture.

	Patient	N_{FE} Right Slow	Medium	Fast	Left Slow	Medium	Fast	N_{AA} Right Slow	Medium	Fast	Left Slow	Medium	Fast	N_{IE} Right Slow	Medium	Fast	Left Slow	Medium	Fast
PND	1	100	25	11	64	11	3	36	17	7	32	7	1	200	33	11	180	19	2
	2	102	25	14	68	15	6	36	16	8	29	11	4	245	33	17	237	27	10
	3	86	31	14	61	22	8	50	22	12	35	6	3	244	48	19	250	30	9
	4	88	44	26	77	26	11	36	25	15	45	17	6	230	75	39	247	37	17
	5	95	39	17	100	37	18	42	22	13	44	13	9	249	49	25	253	48	24
	Mean	94	33	16	74	22	9	40	20	11	37	11	5	234	48	22	233	32	12
	STD	7	8	6	16	10	6	6	4	3	7	4	3	20	17	11	30	11	8
PD	6	94	34	8	72	32	14	29	18	2	22	7	4	156	36	10	137	34	20
	7	87	23	8	80	24	10	29	8	3	37	8	5	195	26	11	133	31	12
	8	91	33	7	71	34	15	27	15	3	21	6	4	152	35	11	134	32	11
	9	144	57	26	143	44	25	54	33	20	46	17	11	281	75	30	237	54	24
	Mean	104	37	12	92	34	16	35	19	7	32	10	6	196	43	16	160	38	17
	STD	27	14	9	35	8	6	13	11	9	12	5	3	60	22	10	51	11	6
	10	103	67	39	112	82	41	35	33	20	58	38	15	280	90	45	279	95	51

Table 7.40: Distribution of the movements per hour for the left and right shoulder for 10 patients at 6 months after surgery for the standing posture.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	94	27	12	84	17	5	32	14	7	26	9	3	137	31	13	130	20	7
PND	2	100	36	21	101	36	15	45	19	10	52	17	7	286	44	28	248	38	23
PND	3	97	37	15	87	27	11	40	21	9	37	15	5	262	44	17	251	32	13
PND	4	91	40	29	58	21	10	47	20	14	21	6	4	240	53	36	217	35	12
PND	5	84	39	13	90	32	12	62	19	8	44	11	5	235	43	17	270	39	19
PND	Mean	93	36	18	84	27	11	45	19	10	36	12	5	232	43	22	223	33	15
PND	STD	6	5	7	16	8	4	11	3	3	13	4	1	57	8	10	55	8	6
	6	112	27	12	74	21	11	38	12	9	82	20	8	199	37	18	190	38	25
	7	79	36	19	116	46	17	44	20	12	41	16	6	237	52	28	197	48	22
	8	53	15	4	68	22	6	28	9	4	50	14	6	213	20	5	179	28	13
	9	110	59	28	129	48	28	60	33	18	48	22	13	251	73	32	233	58	33
	Mean	89	34	16	97	34	16	43	19	11	55	18	8	225	46	21	200	43	23
	STD	28	19	10	30	15	9	13	11	6	18	4	3	23	23	12	23	13	8
PD	10	54	20	10	52	20	7	23	8	7	29	10	8	127	26	14	155	23	8

Table 7.41: Distribution of the movements per hour for the left and right shoulder for 10 patients at baseline after surgery for the sitting posture.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	39	7	4	34	6	1	22	6	2	23	4	1	109	11	2	85	7	2
PND	2	117	18	7	82	11	4	23	6	2	16	4	2	245	18	10	182	14	6
PND	3	101	31	10	63	22	13	31	15	9	20	9	2	215	39	11	167	25	14
PND	4	33	9	5	26	7	2	17	6	4	13	4	2	109	16	7	111	8	4
PND	5	61	24	9	82	17	8	30	11	6	24	9	2	198	21	7	184	17	8
PND	Mean	70	18	7	57	13	6	25	9	5	19	6	2	175	21	7	146	14	7
PND	STD	37	10	3	26	7	5	6	4	3	5	3	0	63	11	4	45	7	5
	6	26	2	1	55	11	2	14	2	1	22	6	2	81	6	1	81	15	5
	7	120	32	6	91	26	7	48	13	1	48	9	1	246	25	17	194	23	7
	8	13	2	0	27	5	2	4	1	1	10	2	1	36	4	1	41	7	3
	9	56	17	4	62	13	4	19	3	2	27	5	1	101	18	2	129	15	8
	Mean	54	13	3	59	14	4	21	5	1	27	6	1	116	13	5	111	15	6
	STD	48	14	3	26	9	2	19	6	1	16	3	1	91	10	8	66	7	2
PD	10	38	16	11	50	12	7	14	9	8	22	6	2	81	19	13	131	18	9

Table 7.42: Distribution of the movements per hour for the left and right shoulder for 10 patients at 3 months after surgery for the sitting posture.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	57	18	9	99	12	1	36	14	4	19	4	0	191	19	11	176	12	2
	2	70	10	6	51	8	2	19	4	3	20	4	1	183	13	7	136	12	3
	3	106	25	10	54	13	2	41	15	6	25	6	1	250	28	14	169	17	4
	4	43	20	12	41	8	7	25	12	7	21	7	2	133	26	13	143	17	6
	5	66	11	6	71	17	9	34	9	6	34	6	3	186	24	9	176	27	10
	Mean	68	17	9	63	12	4	31	11	5	24	5	1	189	22	11	160	17	5
	STD	23	6	3	23	4	4	9	4	2	6	1	1	42	6	3	19	6	3
PD	6	61	10	3	95	19	9	12	3	1	18	8	5	101	10	4	141	24	10
	7	63	15	5	54	8	6	24	12	2	31	4	1	155	19	7	107	13	6
	8	64	13	7	70	15	8	33	8	7	31	5	4	184	21	7	140	22	5
	9	109	31	11	106	20	11	39	17	7	37	7	4	233	43	12	179	24	10
	Mean	74	17	7	81	16	9	27	10	4	29	6	4	168	23	8	142	21	8
	STD	23	9	3	24	5	2	12	6	3	8	2	2	55	14	3	29	5	3
	10	40	13	6	57	14	7	12	7	3	27	8	5	116	20	8	142	23	9

Table 7.43: Distribution of the movements per hour for the left and right shoulder for 10 patients at 6 months after surgery for the sitting posture.

		N_{FE}						N_{AA}						N_{IE}					
		Right			Left			Right			Left			Right			Left		
	Patient	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast	Slow	Medium	Fast
PND	1	55	13	5	58	9	2	21	7	5	22	2	2	91	15	4	90	10	2
	2	76	17	8	82	12	6	49	9	9	45	7	3	208	21	11	157	16	8
	3	81	24	6	77	15	5	31	17	5	25	5	3	152	26	11	112	19	6
	4	57	20	14	44	15	6	36	16	12	24	6	4	162	33	22	120	24	13
	5	62	14	6	49	12	5	37	12	5	30	5	2	194	17	7	135	16	5
	Mean	66	18	8	62	13	5	35	12	7	29	5	3	161	22	11	123	17	7
	STD	12	5	4	17	3	2	10	4	3	9	2	1	45	7	7	25	5	4
PD	6	142	32	12	71	21	20	40	10	10	83	17	10	227	49	19	189	49	39
	7	85	30	9	76	12	6	41	16	7	28	6	3	262	35	11	149	16	7
	8	54	10	1	61	12	5	34	9	1	62	6	2	188	12	3	142	19	8
	9	99	35	15	93	34	22	37	20	16	33	15	6	183	46	22	168	44	24
	Mean	95	27	9	75	20	13	38	14	9	52	11	5	215	36	14	162	32	20
	STD	37	11	6	13	10	9	3	5	6	26	6	4	37	17	9	21	17	15
	10	40	11	4	33	11	7	18	10	4	26	6	4	107	17	5	113	18	6

7.2.3.4 Detection of the working level of the humerus during the daily activity

Using the algorithm described in the chapter 6, we analyzed the working level above the level 5 (L58) for the 10 patients at baseline, 3 and 6 months after surgery. The Table 7.44 shows the difference of number of working levels L58 per hour between the healthy and the painful shoulder for the patients at baseline, 3 and 6 months after surgery, and for the control group.

Table 7.44: Average difference of number of working levels L58 per hour between the painful and the healthy shoulder for the control group and the patients at baseline, 3 and 6 months after surgery.

Levels	P1 Δ	std	P2 Δ	std	P3 Δ	std
L58 control	3.60	15.12	0.17	1.53	-0.05	0.66
Levels	Delta	std	Delta	std	Delta	std
L58 baseline	8.11	31.64	1.91	2.40	0.68	1.08
L58 3 months	19.32	26.53	2.01	5.50	0.32	2.59
L58 6 months	10.85	19.84	0.36	2.72	0.18	0.85

The Table 7.45 shows the relationship between the working levels for the patients with the Constant questionnaires (WLC) and the maximum working level from our method (mWL). All the maximum working levels for the patients were reached during the period P1 (0s-1s). C0 to C4 corresponded respectively to the pelvis, xyphoïd, neck, head and above the head levels.

Table 7.45: Working Level of the Constant questionnaire (WLC) and the maximum level of our method (mWL) for the patients at baseline, 3 and 6 months after surgery.

Patient	Baseline Healthy WLC	mWL	Painful WLC	mWL	3 months Healthy WLC	mWL	Painful WLC	mWL	6 months Healthy WLC	mWL	Painful WLC	mWL
1		L6	C1	L6		L8	C1	L4		L8	C1	L7
2		L7	C1	L5		L7	C2	L5		L7	C2	L6
3		L6	C4	L5		L6	C4	L4		L7	C4	L5
4		L7	C1	L7		L7	C1	L6		L7	C2	L7
5		L8	C2	L4		L7	C2	L6		L6	C4	L6
6	C4	L8	C0	L4	C4	L8	C2	L7	C4	L8	C4	L7
7		L6	C3	L6		L7	C4	L8		L7	C4	L7
8		L8	C0	L6		L7	C3	L8		L8	C1	L5
9		L7	C1	L7		L8	C3	L6		L7	C4	L6
10		L8	C4	L7		L7	C4	L7		L7	C4	L6

The working level part of the Constant score has shown a significant difference between the healthy and the painful side at baseline, 3 and 6 months after surgery ($p<0.04$). The difference between the healthy and the painful shoulder was also significant for the mWL of our method ($p<0.03$). For the comparison between the follow-up and the baseline, the WLC has shown no significant difference ($p>0.06$) between baseline and 3 months but a significant difference appeared at 6 months after surgery ($p<0.02$). The mWL has shown significant differences between baseline and 3, 6 months after surgery ($p<0.001$). There was no difference between 3 months and 6 months after surgery for the WLC ($p>0.4$) but the opposite was occurred for the mWL (Table 7.44 and 7.45). Moreover, we found a low correlation (R=0.44) between the WLC and the mWL.

Table 7.46: Summary of the comparison between the healthy shoulders and the painful shoulders, and between baseline and follow-up for the WLC and mWL.

Healthy/Painful	WLC	mWL
Baseline	p<0.001	p<0.01
3 months	p<0.02	p<0.03
6 months	p<0.04	p<0.01
Baseline/Follow-up	**WLC**	**mWL**
3 months	NS	p<0.01
6 months	p<0.02	p<0.001

The Tables 7.47 to 7.49 show the results for the Working Level Scores at baseline, 3 months and 6 months after surgery. In the chapter 6, we observed a WLS of 100% (±31) in average for the control group. At baseline, 3 and 6 months after surgery, the average WLS was 54% (±17), 77% (±18) and 87% (±21) respectively.

Table 7.47: Working Level Score (WLS) and Weighting scores for the periods P1 (0s-1s), P2 (1s-5s) and P3 (5s-30s) for the patients at baseline.

	Patient	P1	P2	P3	WP	P1	P2	P3	WH	WLS
PND	1	15	20	18	53	36	20	20	86	62
PND	2	10	20	18	48	28	30	45	103	47
PND	3	10	12	9	31	15	20	18	53	58
PND	4	15	12	18	45	28	30	30	88	51
PND	5	10	12	18	40	36	30	45	111	36
		P1	P2	P3	WH	P1	P2	P3	WP	WLS
PD	6	36	56	57	149	10	20	18	48	32
PD	7	21	30	30	81	21	20	9	50	62
PD	8	36	58	54	148	21	20	18	59	40
PD	9	28	30	18	76	21	30	18	69	91
		P1	P2	P3	WP	P1	P2	P3	WH	WLS
PD	10	21	42	45	108	21	20	30	71	66

Table 7.48: Working Level Score (WLS) and Weighting scores for the periods P1 (0s-1s), P2 (1s-5s) and P3 (5s-30s) for the patients at 3 months.

	Patient	P1	P2	P3	WP	P1	P2	P3	WH	WLS
PND	1	10	20	18	48	28	20	30	78	62
PND	2	21	12	18	51	21	30	18	69	74
PND	3	15	20	18	53	21	30	9	60	88
PND	4	28	12	18	58	28	30	30	88	66
PND	5	21	20	30	71	21	30	30	81	88
		P1	P2	P3	WH	P1	P2	P3	WP	WLS
PD	6	36	72	108	216	21	42	63	126	58
PD	7	28	30	45	103	36	30	45	111	108
PD	8	36	30	18	84	15	20	18	53	63
PD	9	28	20	30	78	21	30	30	81	104
		P1	P2	P3	WP	P1	P2	P3	WH	WLS
PD	10	22	44	66	132	21	30	30	81	61

Table 7.49: Working Level Score (WLS) and Weighting scores for the periods P1 (0s-1s), P2 (1s-5s) and P3 (5s-30s) for the patients at 6 months.

	Patient	P1	P2	P3	WP	P1	P2	P3	WH	WLS
PND	1	15	12	9	36	15	20	18	53	68
PND	2	15	30	18	63	28	30	21	79	80
PND	3	15	30	30	75	28	30	30	88	85
PND	4	28	12	18	58	28	34	18	80	73
PND	5	21	42	33	96	21	42	63	126	76
		P1	P2	P3	WH	P1	P2	P3	WP	WLS
PD	6	36	42	18	96	21	20	18	59	61
PD	7	21	20	18	59	21	20	30	71	120
PD	8	15	20	18	53	21	30	9	60	113
PD	9	28	20	30	78	15	30	45	90	115
		P1	P2	P3	WP	P1	P2	P3	WH	WLS
PD	10	36	44	30	110	21	30	30	81	74

At baseline and 3 months after treatment, we observed a significant difference (p<0.03) between the healthy and the painful side for the weighting scores of the periods P1, P2, and P3, and we observed a significant difference for the WLS between the control group and the patients (p<0.01) (Table 7.50).

At 6 months after surgery, we observed no significant difference (p>0.15) between the healthy and the painful side for the weighting scores of the periods P1, P2 and P3 and the WLS.

Table 7.50: Summary of the comparison between the healthy shoulders and the painful shoulders, and between baseline and follow-up for the WLS.

Healthy/Painful	WLS
Baseline	p<0.01
3 months	p<0.03
6 months	NS
Baseline/Follow-up	**WLS**
3 months	p<0.01
6 months	p<0.004

No significant difference appeared for the comparison fof the evolution of the WLS between 3 months and 6 months after surgery (p>0.1). Moreover, a fair correlation was observed (R=0.59) between the WLS and the Constant score.

7.2.4 Discussion

7.2.4.1 Clinical scores

The clinical scores (DASH, SST, Constant, ASES) are the most recognized scores for the evaluation of the functionality of the shoulder. We observed in the Tables 7.14 to 7.16 a tendency for these clinical scores (except the balanced Constant score) to be less responsive than the method we proposed. Indeed, significant differences were shown for the comparison between the patients' group and the control group at baseline and follow-up, but no significant difference was found between baseline and follow-up. Moreover, these clinical scores are linked to the patients' answers and did not give an objective evaluation of the functionality of the shoulder during the daily activity. No clinical scores assessed the number of movements performed during a day, the real contribution of the non dominant and dominant shoulder and the real working level and the endurance to work at a specific level. These clinical scores are useful to have an evaluation on what the patient can do, but not on what the patient does actually. Moreover, their sensitivity to change are not always enough in estimating the evaluation of the shoulder function after surgery.

7.2.4.2 Estimation of the dominant shoulder during daily activity

Using the algorithm described in the chapter 4, we estimated which shoulder was more active for the 10 patients before surgery, 3 and 6 months after surgery (Tables 7.18 to 7.20).

At baseline, the patients of the PD group used more their non dominant shoulder during the sitting, standing and walking (in average +14%). Indeed, their painful shoulder was the dominant one. The patient of the PND group used more their dominant shoulder as predicted, because their painful shoulder was the non dominant one. But, during the walk they used more the non painful shoulder. The patient of the PND group used their dominant shoulders much more (in average +24 %) compared to the healthy group (in average +18%) (Table 7.17).

We can conclude that if a patient had a disease to his dominant shoulder, he used more his non dominant shoulder during the daily activity, while, for a patient with a disease to his non dominant shoulder, he will use his dominant shoulder much more than usual during (Table 7.18).

Three months after surgery, the tendency is almost the same for the PND at baseline (+31%), while, for the PD group, the tendency seems to be reversed: the healthy non dominant shoulder was in average 7% more active than the painful dominant shoulder. Albeit, for the standing position, the shoulders had the same rate of activity (Table 7.19).

Six months after surgery, the dominant shoulders of the PD group's patients retrieved their "dominance". The painful dominant shoulder was in average 12 % more active than the non painful shoulder. The PND group still used its dominant shoulder (in average 26 %) more than the healthy group (Table 7.20). The reason of the small p value (p=0.053) for the difference between the healthy and the painful side at 6 months after surgery for the sitting/standing periods could be to the small number of patients. A larger number of patients could decrease this value to show a significant difference.

The Figure 7.3 shows the evolution of the functionality of the painful dominant shoulder for the right-handed patient of the PND group.

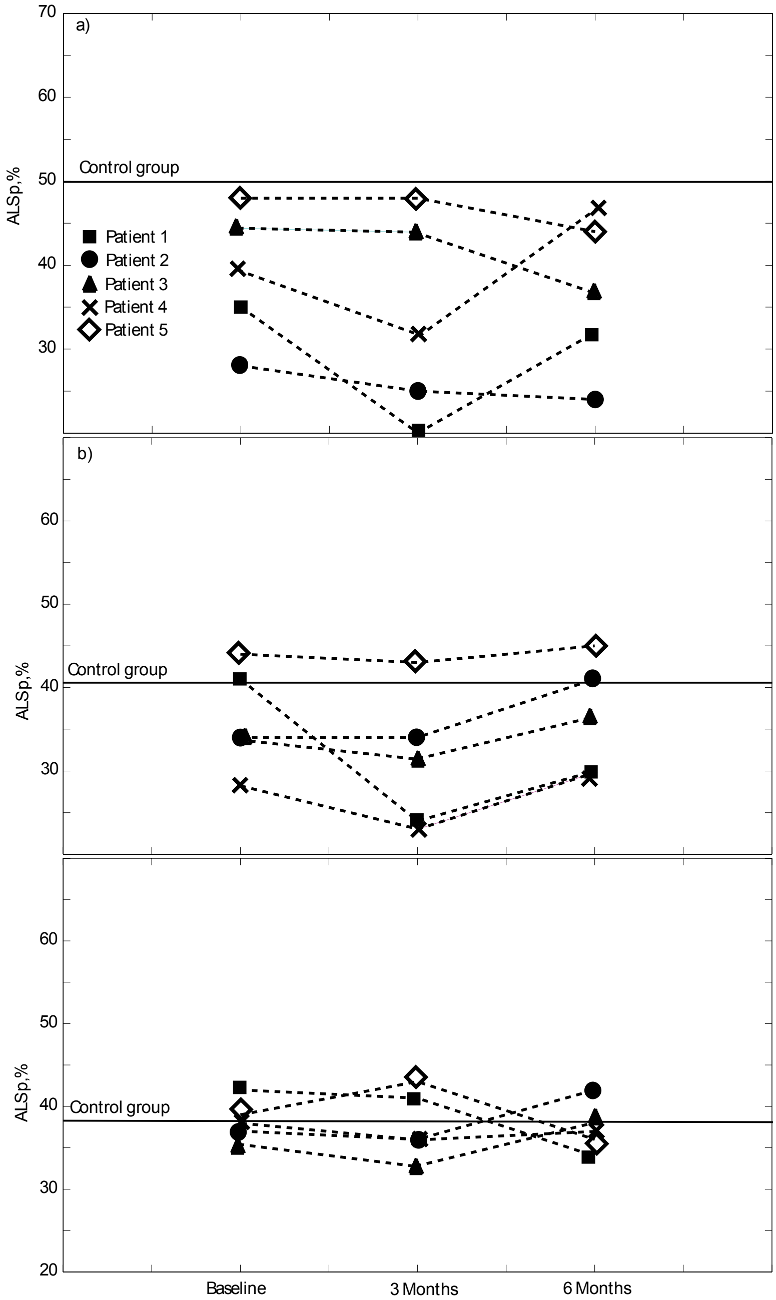

Figure 7.3: The evolution of the functionality of the painful dominant shoulder for the right-handed patient of the PND group for a) walking, b) standing and c) sitting.

All right-handed patients of the PD group retrieved their functionality of their dominant shoulder at 6 months after surgery. Their rate reached almost the rate of the right shoulder of the right-handed control subjects and they were higher than the baseline (Figure 7.4).

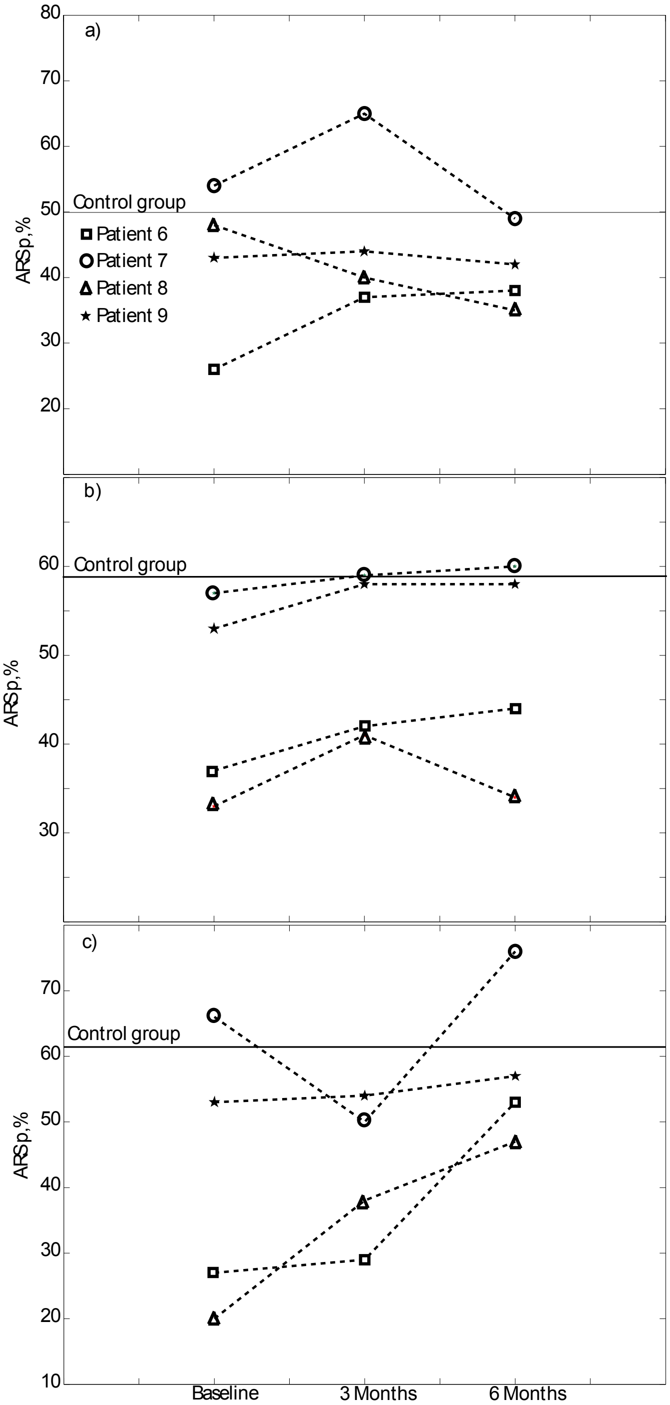

Figure 7.4: The evolution of the functionality of the painful dominant shoulder for the right-handed patient of the PD group for a) walking, b) standing and c) sitting.

The left-handed patients of the PD group retrieved their functionality of their dominant shoulder at 6 months after surgery. Their rate reached almost the rate of the left shoulder of the left-handed control subjects or they were higher than the baseline (Figure 7.5).

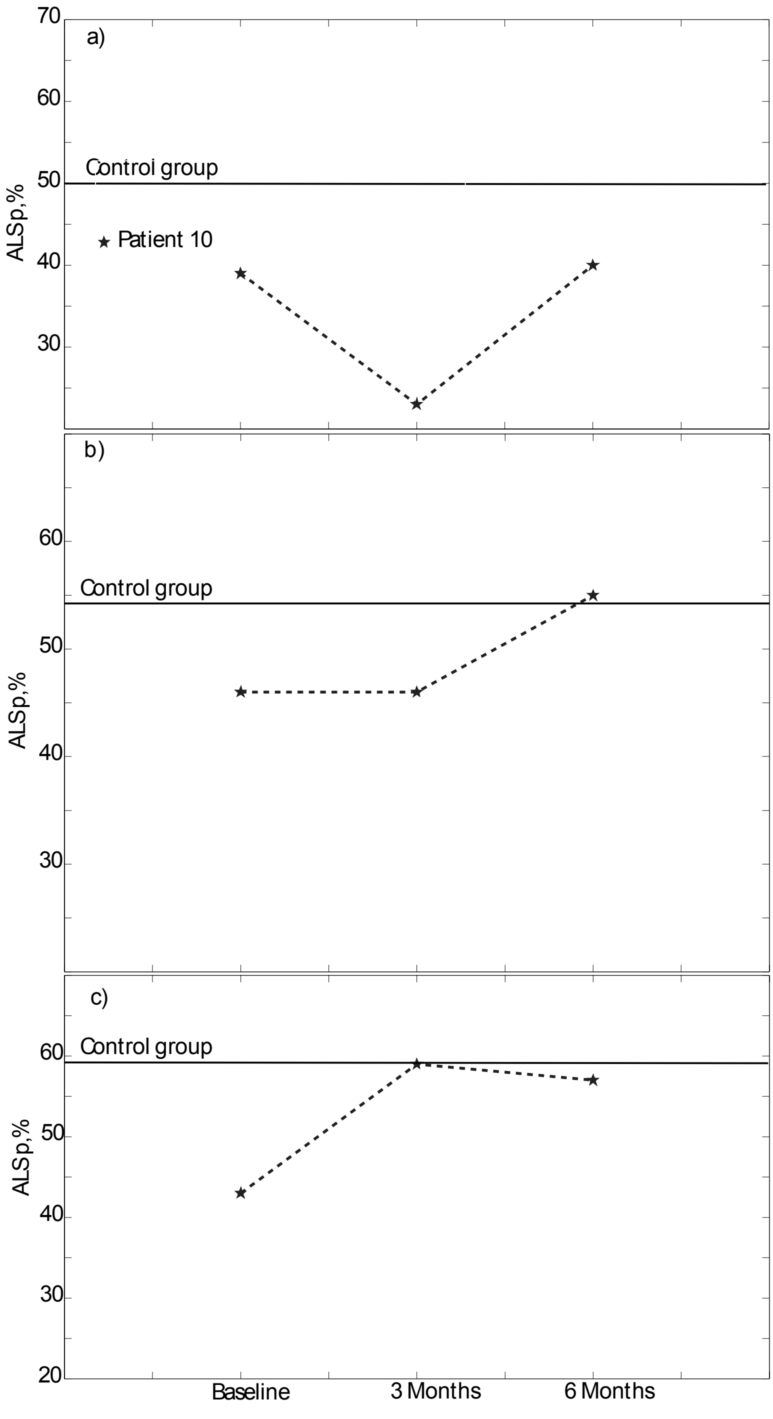

Figure 7.5: The evolution of the functionality of the painful dominant shoulder for the left-handed patient of the PD group for a) walking, b) standing and c) sitting.

We have the same observation for the value of the mean P (Table 7.22). The patients of the PD group had a mean P value greater for the healthy non dominant shoulder than the painful dominant shoulder at baseline. But the tendency is reverted at 3 and 6 months after surgery. The patients of the PND group had a mean P value greater at 6 months than at baseline, but the mean P value is still greater for the healthy dominant shoulder than the painful non dominant shoulder at baseline, 3 and 6 months after surgery.

We expect that 12 months after surgery the patients will retrieve a normal functionality of their operated shoulder.

7.2.4.3 Characterization of the movement of the humerus during daily activity

A. Number of flexions, abductions and int/ext rotations per hour

Using the algorithm described in the chapter 5, we estimated the differences of number of movements (flexion (N_{FE}), abduction (N_{AA}) and int/ext rotation (N_{IE})) of the humerus between the healthy and the painful shoulder for the 10 patients (Tables 7.24 to 7.26).

Before surgery, we observed that the patients of the PD group performed more movements with their healthy non dominant shoulder than their painful dominant shoulder. Their dominant shoulder lost its predominance in favor of the healthy shoulder, the non dominant shoulder. The patients of the PND group performed more movements with their healthy dominant shoulder as expected (Figure 7.6 a)).

At 3 and 6 months after surgery, the tendency is reverted. The patients of the PD group performed slightly more movements with their dominant shoulder. Their dominant shoulder retrieved its predominance (Figures 7.6 b) and c)) after treatment.

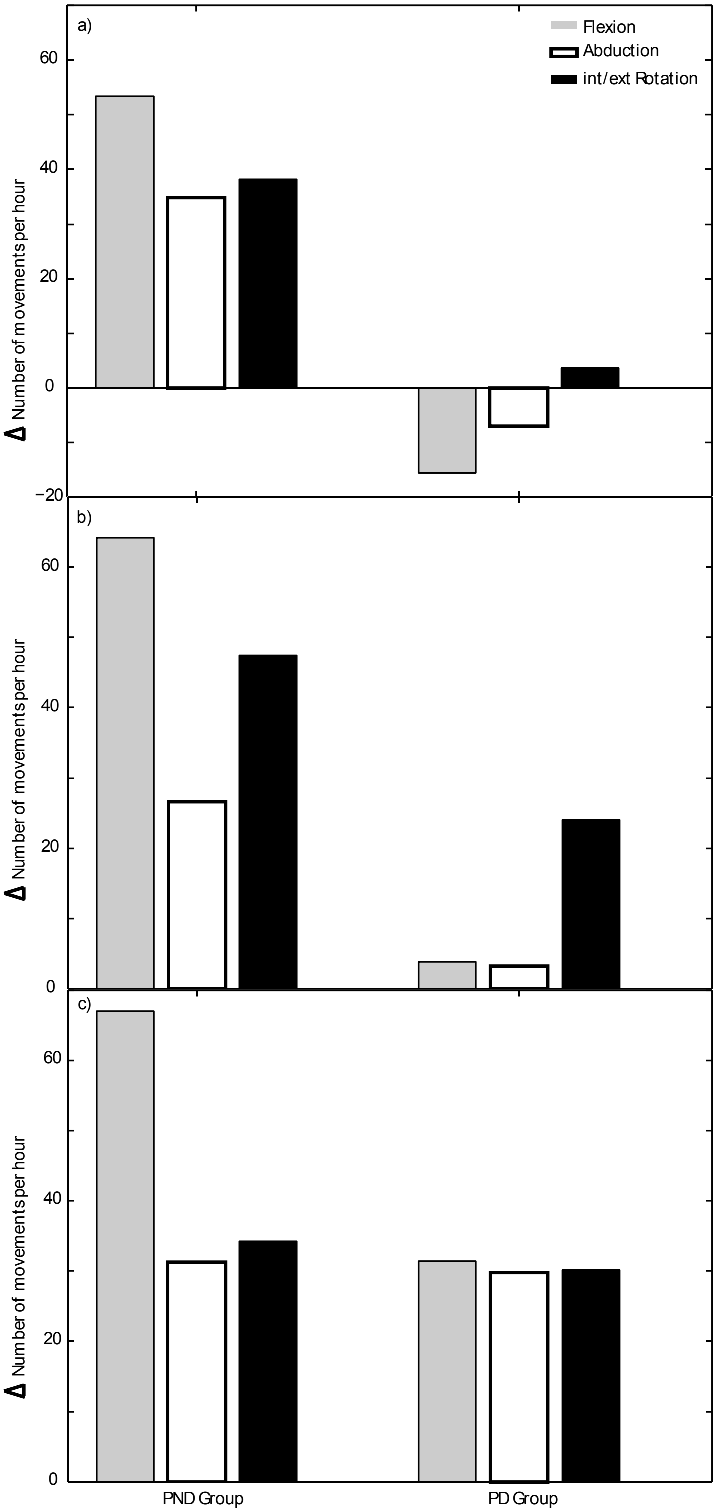

Figure 7.6: Difference of the number of flexions, abductions and int/ext rotations per hour between the dominant shoulder and the non dominant shoulder for the 10 patients for all activities at a)Baseline, b) 3 months after surgery and c) 6 months after surgery.

B. *Combination of the adjunct and conjunct rotation*

The results in the chapter 5 showed that there was no difference between the dominant humerus and the non dominant humerus for the healthy subjects. So, we compared the PS and HS group. At baseline, the only difference was for the contribution of the IE movement. There was less IE rotation for the PS group (Table 7.28). Indeed, the patients with a tear in a rotator cuff tendon have a pain or a weakness on internal or external rotation of the humerus[2].

At 3 and 6 months after surgery, the patients retrieved a normal contribution of the IE rotation.

C. *Angular velocity distribution of the flexion, abduction and int/ext rotation*

At baseline, we found a significant difference between the PS group and the HS group for the fast flexion, abduction and int/ext rotation. The healthy shoulders performed more movements above 100°/s than the painful shoulders.

At 3 and 6 months after surgery, the painful shoulders had the same angular distribution than the healthy shoulders. The angular velocity of the humerus of the painful side increased after surgery.

A typical healthy subject has the same angular velocity distribution for the flexion, abduction and int/ext rotation for the dominant shoulder and the non dominant shoulder. The predominance does not matter for the angular velocity distribution of the movements. For a typical patient, there are less fast movements (higher than 100°/s) for the painful shoulder at baseline. At 3 months after surgery, the patients will perform again fast movements.

7.2.4.4 Detection of the working level of the humerus during the daily activity

Using the algorithm described in the chapter 6, we estimated the ability for the 10 patients to work at a specific level with the humerus and compared it between the healthy side and the painful side (Tables 7.44).

The difference of number of the working levels L58 per hour between the healthy and the painful shoulders showed that the frequency of the working levels reached above the shoulder decreased for the painful side at baseline and 3 months after surgery. The tendency is inverted at 6 months after surgery. The painful side still reached a lower working level than the healthy side but the difference decreased (Δbaseline = 8.1; Δ3months = 19.3; Δ6months = 10.8) (Table 7.44). We expect that the patient will have, as the control group, almost the same number of working levels per hour for his painful shoulder at 12 months after surgery.

Compared to the mWL, there was no significant difference for the WLC between the baseline and 3 months after surgery (p=0.062). The small number of patients and the poor sensitivity of the WLC can explain this p value. But also, this difference can be explain by the fact that WLC corresponds to what a patient considers to be able to do, while mWL expresses what he or she has really do. The mWL is rather high even for painful side (Table 7.46), probably because of the fact that the maximum of the working level reached is taken. We proposed a more significant method by choosing the maximum level to balance by the duration: WLS.

Compared to the Constant score, the WLS score showed a better responsiveness to the variation of the activity of the shoulder. Indeed, the WLS showed a significant difference at 6 months after surgery compared to the Constant score which showed no significant difference.

The evolution of the ability of working at a specific a level can be shown with the WLS (Figure 7.7). Improvements are shown between the preoperative and the postoperative periods (3 and 6 months).

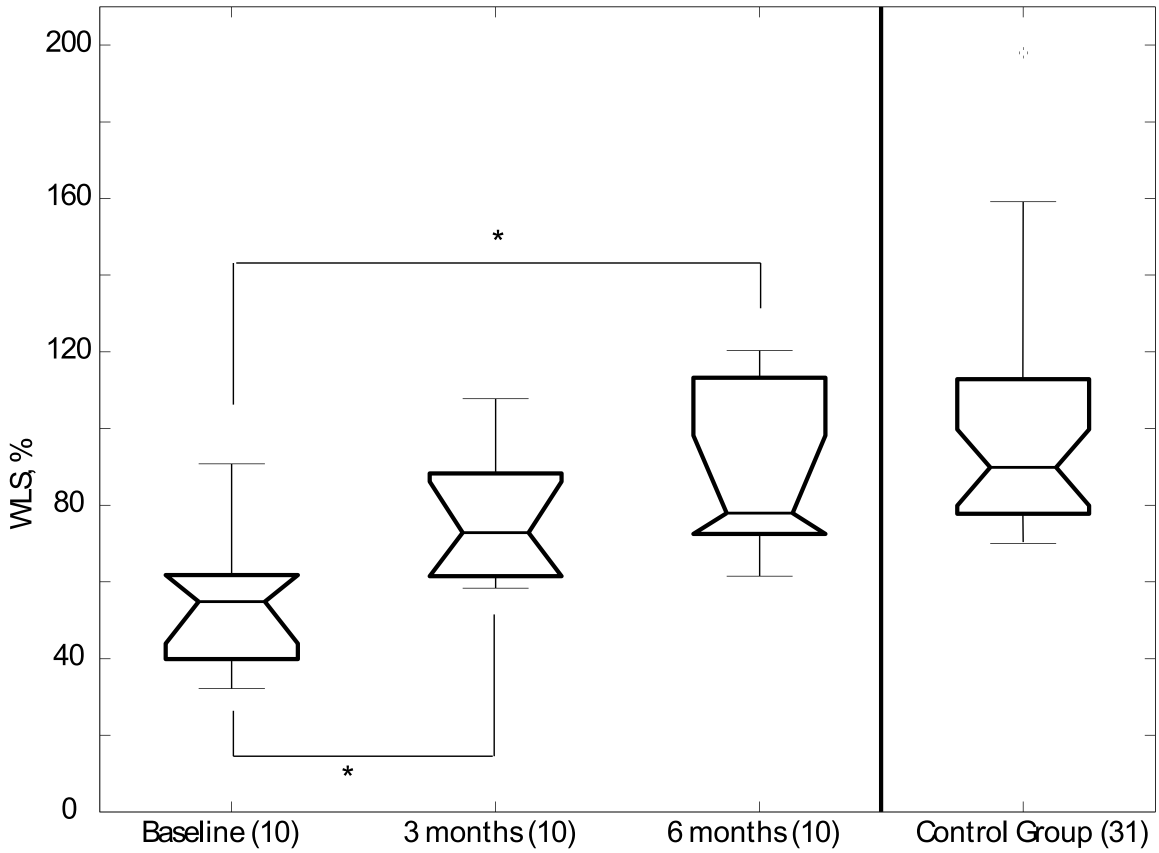

Figure 7.7: The WLS for the control group and for the patients at baseline, 3 and 6 months after surgery.

7.2.5 Conclusion

We described three different methods of assessing the functionality of the shoulder during daily activity: one to assess the dominant segment and its intensity to move, one to estimate the number of flexions, abductions and int/ext rotations per hour and one to assess the working level and the endurance of the shoulder.

Even the sample size is too small, the results showed interesting tendencies that should be very useful for further studies on the shoulder and for the choice of outcome tool in clinical practice. Major results regarding the outcome evaluation of the patient after the shoulder surgery are summarized in Table 7.51.

Table 7.51: Summary of the comparison between the healthy and the painful shoulders, and between baseline and follow-up for the WLS.

Patient with a disease at the dominant side	***Patient with a disease at the non dominant side***
Estimation of the dominant shoulder during daily activity	
Baseline: • The non dominant side was used more than the dominant side. • The intensity was higher on the non dominant side. 3 months after surgery: • The dominant side was used at almost the same rate as the non dominant side. • The intensity was higher than baseline but still less than the non dominant. 6 months after surgery: • The dominant side was used more than the non dominant. The tendency was reserved. • The intensity was higher than the non dominant side and than 3 months.	Baseline: • The dominant side was used more than the normality. • The intensity was higher on the dominant side. 3 months after surgery: • The non dominant side was used more than baseline, but still less than the normality. • The intensity was higher on the dominant side. 6 months after surgery: • The non dominant side was used as the same rate as the normality. • The intensity was still higher on the dominant side.
Characterization of the movement of the humerus during daily activity	
Baseline: • The number of flexion, abduction and int/ext rotation per hour was higher for the non dominant side. • There was less number of movement for the fast movement for the painful side. • There was less IE conjunct rotation for the painful side. 3 months after surgery: • There was almost the same number of movements for the painful dominant side and the healthy non dominant side. • There was less number of	Baseline: • The number of flexion, abduction and int/ext rotation per hour was higher for the dominant side. • There was less number of movement for the fast movement for the painful side. • There was less IE conjunct rotation for the painful side. 3 months after surgery: • There was more number movements for the dominant side than baseline. • There was less number of movements for the fast movement for the painful side. • There was no difference between the

<table>
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<td>
<li style="list-style:none">movements for the fast movement for the painful side.
There was no difference between the dominant and the non dominant side for the combination of rotations.
6 months after surgery:
There was more number of movements per hour for the dominant side than the healthy non dominant side.
The angular velocity distribution of the number of movements was the same for both arms.
There was no difference between the dominant and the non dominant side for the combination of rotations.
</td>
<td>
<li style="list-style:none">dominant and non dominant side for the combination of rotations.
6 months after surgery:
There was more number of movements per hour for the dominant side than the non dominant side.
The angular velocity distribution of the number of movement was the same for both arms.
There was no difference between the dominant and the non dominant side for the combination of rotations.
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<tr>
<td colspan="2" align="center">Detection of the working level of the humerus during the daily activity</td>
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<td colspan="2">
Baseline:
The painful side had less number of working levels above the shoulder than the healthy side.
The WLS score was very low compared to the control group.
3 months after surgery:
The painful side had still less number of working levels per hour above the shoulder than the healthy side.
The WLS score was higher than at baseline but was still lower than the control group.
6 months after surgery:
The painful side had almost the same number of working levels above the shoulder.
The WLS score was higher than 3 months after surgery and closer of the control group.
</td>
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</table>

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Chapter 8 General discussion and future prospects

8.1 General results and main contributions

The objective of this thesis was to design an objective outcome evaluation of the shoulder after surgery that can be used for clinical practice. The project intended to evaluate the use of movement recording with body-fixed inertial sensors for the assessment of the functionality of the shoulder in patient suffering from rotator cuff disease or osteoarthritis based on monitoring of the daily physical activity. The main results and contributions of this thesis can be summarized as follows:

1. *Ambulatory recording system.*

   A specific sensor-based motion recorder system was designed. It was an ambulatory system that can be used for long-term monitoring without hindrance to natural activities. The shoulder movements were captured with five inertial sensor modules using 3D accelerometers and 3D gyroscopes. The sensor modules were mounted on each distal part of both humerus, on the superior part of both scapula's spines and on the thorax. This system corresponds to the actual needs of clinicians, physical therapists and orthopedics surgeons to provide an objective outcome evaluation of the shoulder after surgery. It allows long-term measurements as well as short-term measurements.

2. *Kinematic scores for the short-term evaluation of the shoulder's functionality.*

   Three different kinematic scores were proposed. The P score was based on the combination of the accelerations and the angular velocities of the humerus. The RAV score was based on the range of the angular velocity of the humerus and the M score was based on the sum of all moments on the humerus. 26 patients with rotator cuff disease or osteoarthritis, and 31 healthy subjects were studied. These scores were based on 9 simple tests that can be carried out in a clinical or hospital environment or at home. An objective score can be established this way in a short time by the doctor at each patient's visit. The results showed that the kinematic scores can show objectively the improvement after surgery. The results of this study have been published in a journal article[1].

3. *Estimation of the difference between the movement intensity of the dominant and the non dominant arm in healthy subjects and patients during daily activity.*

   Using an extension of the P score during daily activity, we developed a new method to evaluate the dominant upper-limb segment. 10 patients with rotator cuff disease at baseline, 3 and 6 months after surgery and 31 healthy subjects, who carried our system during ~8 hours, were studied. The method can quantify the difference between the dominant and the non dominant side for a healthy subject, and between healthy and painful side for the patient during the walking, sitting and standing periods. Data showed that the subjects used their dominant upper-limb 18% more than the non dominant upper-limb. The measurements on patients have shown that they have used more their non affected and non dominant side during daily activity if the dominant side = affected shoulder. If the dominant side ≠ affected shoulder, the difference can be shown only during the walking period. The estimation of the dominant side can be used for other applications. In fact, this system can detect what kind of work or activity can generate a problem of the shoulder. For example, a house painter uses more his dominant side than a secretary. The results of this study have been published in a journal article[2].

4. *Identification of the type of the movement of the humerus and its characterization during daily activity.*

   Using 3D gyroscopes attached on the humerus, we have detected the number of movements of flexion, abduction and internal/external rotations per hour. The method was validated in a laboratory setting and then tested on 31 healthy volunteer subjects without any shoulder pathologies and on 10 patients with rotator cuff disease while carrying the system during ~8 hours of their daily life.

We were also able to evaluate the combination rate of adjunct and conjunct rotations and the angular velocity distribution of the movements per hour. We have observed that there was no significant difference for the number of movements per hour, the combination rate of adjunct and conjunct rotations and the angular velocity distribution between the dominant and the non dominant side for the healthy subjects, but the difference was observed for the patients between the healthy and the painful side. The number of movement per hour, the angular velocity distribution increased after treatment. This method is complementary to the method of the estimation of the dominant upper-limb segment. Indeed, we can estimate the type of the movements that the dominant and the non dominant humerus have done during daily activity. This method can also be useful for different medical applications. For example, for a patient who had a small number of internal/external rotations per hour, a physiotherapist can adapt his treatment to increase the number of this kind of movements. The results of this study have been submitted for publication[3].

5. *Estimation of the working level of the shoulder during daily activity.*

   We developed a new method of assessing the working level of the shoulder during daily activity. We were able to estimate the dominant upper-limb segment, its number of movements per hour and, with this method, the working level during daily activity. The method was validated in a laboratory with 5 healthy subjects. 31 healthy subjects and 10 patients at baseline, and 3 and 6 months after surgery were studied during their daily activities. We evaluated the number of working levels per hour during three different periods (P1: 0s-1s; P2: 1s-5s; P3: 5s-30s). We observed that the frequency of the working levels above the shoulder was less for the painful side than the healthy side. The tendency is inverted at 6 months after surgery. We developed the Working Level Score (WLS) that is based on the endurance of the shoulder to work at a specific level. Improvements of the WLS are shown between the preoperative and the postoperative periods (3 and 6 months). Compared to the clinical evaluation using questionnaires (e.g. the Constant score), the WLS score, based on the endurance (frequency + duration) of the shoulder, gives an objective evaluation of the working level during daily activity. This way, it provides what the patient has really performed during daily activity instead of the patient evaluation of his ability to perform a task. The results of this study have been submitted for publication[4].

6. *Clinical protocols and a database of movement patterns.*

Two clinical studies were performed using our ambulatory system. The first protocol (short-term measurement) was conducted on 31 healthy subjects and on 26 patients. Preoperative results were compared with postoperative results (3 months, 6 months and 1 year). Each measurement lasted 6 minutes per subject/patient. As a result, a 14-hour database of different movement patterns was created. The second protocol (long-term measurement) was conducted on the 31 healthy subjects of the first protocol, and on ten new patients with a rotator cuff disease. Each patient/subject wore the ambulatory system during ~8 hours. We proposed the following objective parameters for outcome evaluation: the number of movements (flexion, abduction and internal/external rotation) per hour, angular velocity distribution of the movement per hour, the working level of the humerus, the Working Level Score (WLS) and the estimation of the dominant upper-limb segment. A 449-hour database of long-term measurement was created. These results cannot be obtained through other clinical evaluations and complement the clinical scores with a useful objective dynamic evaluation. These results could be used for further clinical analysis on more patients. Clinicians can used the results of the clinical scores on patients with osteoarthritis or rotator cuff disease as well as our kinematics parameters as references for other studies.

8.2 Future researches

The thesis can be extended to the following directions:

8.2.1 Multi-segments model

A potential improvement of these tools would be to add a 3D model of each segment of the shoulder girdle and to study the inter-action between them during daily activity. The knowledge of the scapula movement and the glenohumeral to scapulothoracic (GH:ST) ratio could be useful to evaluate the functionality of a patient's shoulder. One of our current studies, using our shoulder measurement system, evaluated the GH:ST ratio of 2.2:1 in accordance to the literature[5,6,7]on 10 healthy subjects (Figure 8.1).

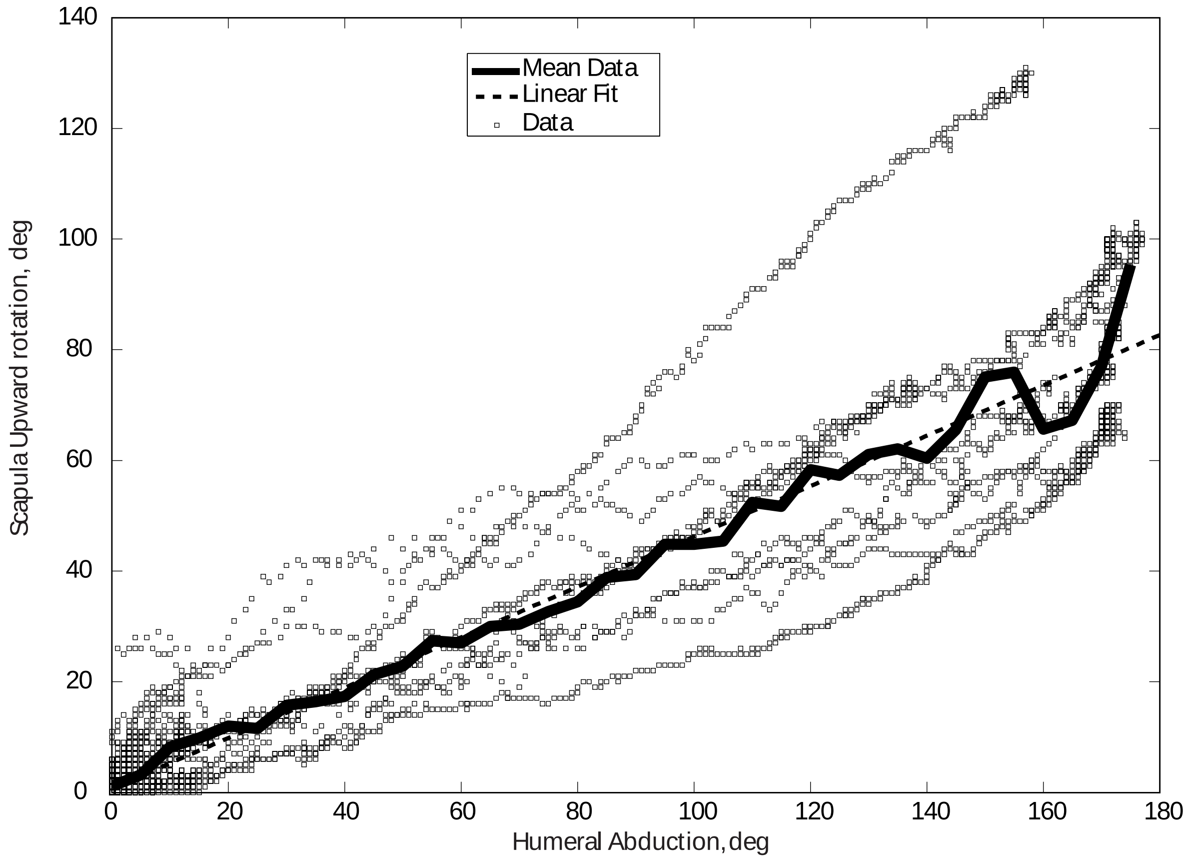

Figure 8.1: Contribution of the glenohumeral and scapulothoracic joints to arm motion for 10 subjects. There is 2.2° of glenohumeral motion every 1° of scapulothoracic motion during abduction.

The inertial modules on the spine of the scapula and on the humerus were used. The abduction and adduction movements of the humerus and the lateral rotations of the scapula were estimated from 3D accelerometers and 3D gyroscopes. This method needs to be more accurate and validated, for example, by fluoroscopy techniques (Roentgen Stereo Photogrametric Analysis, RSA).

Furthermore, some other researchers have a finite element shoulder model[8,9,10] to evaluate force distribution in joint. Usually, they used flexion, abduction and internal/external rotations values from literatures to estimate the forces. The knowledge of the 3D movements of the clavicle, humerus, forearm and scapula associated to our daily activity data could be useful to measure more accurately the force, torque and moment on the shoulder girdle and will increase the reliability of these measures.

8.2.2 EMG for detecting the load

Another interesting direction is to use the inertial sensors with EMG sensors to evaluate the influence of a load on the shoulder. We showed in the chapter 4, 5 and 6 the issue regarding of carrying a load during daily activity. One of our current studies showed that the difference between walking with and without a bag was considerable for the deltoid and trapezius muscle (Figure 8.2 and 8.3).

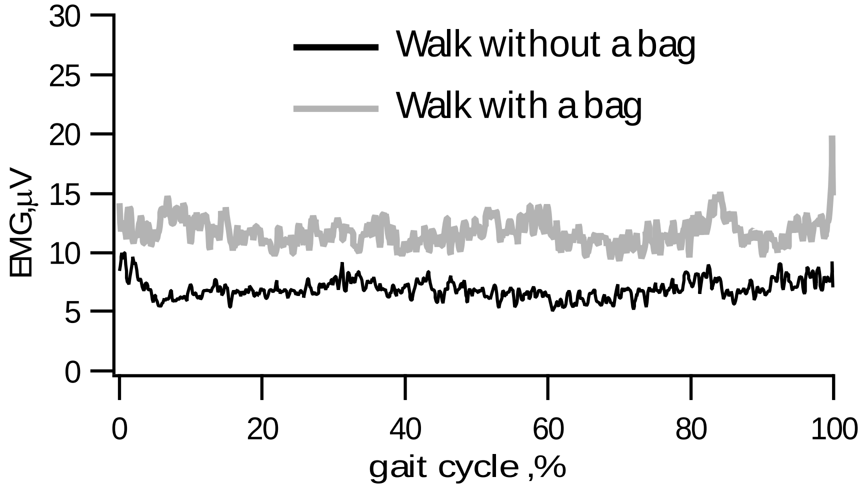

Figure 8.2: EMG average for all subject for the deltoid.

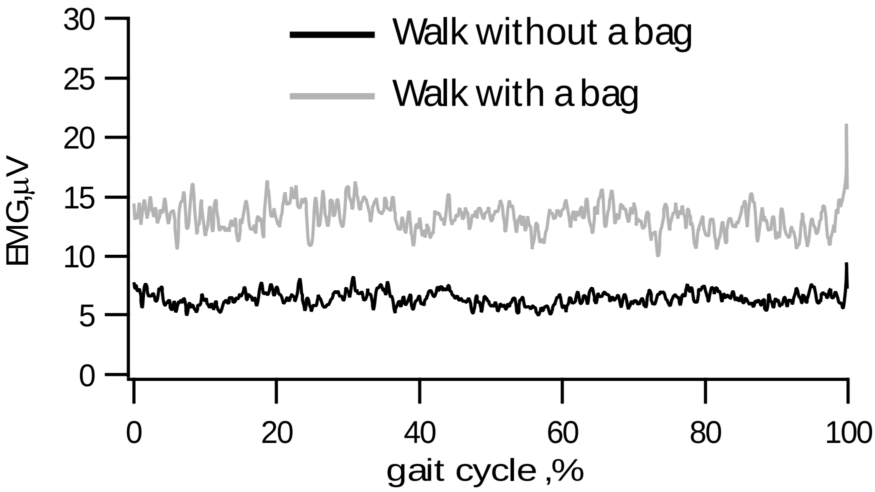

Figure 8.3: EMG average for all subject for the trapezius.

An improvement would be to estimate the limit of kinematics in a functional evaluation by assessing the correlation between kinematics and kinetics parameters and how these correlation change in a pathological case, and secondly, to improve the kinematics evaluation of the segments where inertial sensors are less accurate (e.g. scapula), by considering the muscle activation involved in the movement of such a segment. A new grant from the Swiss national foundation (NRP 53: Musculoskelethal health –chronic pain) was accorded to this study.

8.2.3 Use of our methods for other studies

We have developed new methods to evaluate the number of movements (flexion, abduction and internal/external rotation) per hour, estimate the dominant upper-limb segment and evaluate the working level of the shoulder. The detection method of the number of movements per hour can be easily adapted to other body segments, such as the forearm or the lower limbs. In robotic, the invariability of the rate of conjunct and adjunct rotations could be useful to simulate the movement of the humerus. The method of estimating the dominant segment could be extended to other segments like the forearm, the hand or the lower-limbs. The algorithm to detect motionless periods for the evaluation of the working level could also be used in other body segments, for example, in trunk, to evaluate trunk sway in subject with balance impairment. These results regarding the statistic of the motionless periods (Figure 6.7) reveal a new insight of rest/activity distributions of the body segments over a long period of recording. These results can also be exploited by considering the long-term correlation in the segment mobility (e.g. self similarity and fractal analysis).

A fractal analysis could be done on the working level distribution and the distribution of the movements per hour. A combination between the detection of the working level and the movement of the humerus could estimate the value of the angle of these movements.

An other application would be to estimate the type of movement (FE, AA or IE) performed to reach a working level. This way, it will be possible to estimate for each working level the 3D angles.

Finally, the hardware can be improved and further developed to design a wearable system which will be totally a non obtrusive device that allows physicians to overcome the limitations of ambulatory technology and provide a response to the need for monitoring individuals over weeks or even months.

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Nomenclature

Frequently used symbols and abbreviations:

3D	Three dimensional
t	Time
s	Second
ms	Millisecond
g	gravitational acceleration (9 = 9.81 m/s^2)
ω	Angular velocity
a_v	Vertical acceleration
m/s	Meter / second
yrs	Years old
max	Maximum
min	Minimum
p	Probability
NS	Non significant
R	Correlation factor
RMS	Root Mean Square
th	Threshold for the detection of the movements of the humerus
thp	Threshold for estimating dominant shoulder
STD	Standard Deviation
TP	True Positive
TN	True Negative
FP	False Positive
FN	False Negative
ICC	InterClass Correlation
P	Kinematic score based on the product of the acceleration range by the angular velocity range
RAV	Range of Angular Velocity. Kinematic score based on the angular velocities
M	Kinematic score based on the sum of all moments on the humerus
I	Inertial matrix
L_h	Length of the humerus
C_h	circumference of the biceps
m	Mass of the humerus
Working level	Ability to work at a specific level
ARS	Right shoulder usage rate
ALS	Left shoulder usage rate
Intensity	Combination of accelerations and angular velocities to characterize a movement
D	Dominant
ND	Non Dominant

AA	Abduction-Adduction
FE	Flexion-Extension
IE	Internal/External rotation
N_{AA}	Number of abduction-adduction
N_{FE}	Number of flexion-extension
N_{IE}	Number of internal/external rotation
Adjunct rotation	Voluntary rotation
Conjunct rotation	Automatic rotation
Li	Level i (i = 0:8)
Pj	Period j (j = 1 :3)
WS	Weighting Score
WLS	Working Level Score
GH:ST	Glenohumeral to scapulothoracic ratio
EMG	Electromyogram
RSA	Roentgen Stereo photogrametric Analysis
DASH	Disabilities of the Arm, Shoulder and Hand
SST	Simple Shoulder Test
ASES	American Shoulder and Elbow Surgeons Evaluation
VAS	Visual Analog Scale
BMI	Body Mass Index
Ri	Right
Le	Left
A	Osteoarthritis
C	Rotator cuff disease
MEMS	Micro Electro Mechanical Systems
WLAN	Wireless Local Area Network

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Diploma of operational manager (PMI), CEFCO, Lausanne — 2005-2006

Master in electronics engineering, EPFL, Lausanne — 1998-2003
- Diploma project: “Estimation of the displacements of the lower limbs amputees“.
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WORK EXPERIENCE

Project manager, LMAM, EPFL, Lausanne — 2005-2006
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Matlab, LabView, C, C++, Java, MS Project, Word, Excel, PowerPoint.

PUBLICATIONS

Journal papers

Coley B, Jolles BM, Farron A, Aminian K. Working level of the shoulder during daily activity. Gait & Posture 2007; In Press.

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