A Monitoring System to Reduce Shoulder Injury Among Construction Workers

by

Abdullatif Alwasel

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Systems Design Engineering

Waterloo, Ontario, Canada, 2011
©Abdullatif Alwasel 2011

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abdullatif Alwasel

Abstract

As the work force ages and workers' retirement age increases, the number of workers suffering from Work-related Musculoskeletal Disorders (WMSDs) has increased. In a recent study, the U.S Bureau of Labor reported that 6.9% of all WMSDs affected shoulders. Electricians, carpenters, and related construction crafts appear to experience higher incidence of these injuries due to work that requires awkward shoulder postures. This research aims to develop a new monitoring system that measure the amount of time workers spend in awkward shoulder postures to help decrease the prevalence of cumulative shoulder injuries among construction workers.

A shoulder posture monitoring system was designed and a feasibility study was carried out to compare the system performance with that of a state of the art motion tracking system. Overall the monitoring system was able to perform as a discrete state sensor classifying the worker shoulder posture into safe or an awkward bin during each sampling period. While the monitoring system was implemented experimentally in a laboratory environment, test results indicate that the system in its current configuration is not robust enough for field deployment. Further research and development is recommended to reconfigure the monitoring system and its angle sensing element to produce quantitatively valid human joint angle measurements that can be used in the fields of biomechanics, robotics, and ergonomics.

Acknowledgements

First of all, I would like to thank Allah, the Almighty, for guiding me and having made everything possible to do this thesis. I would like to thank my supervisors, Professor Eihab Abdel-Rahman and Professor Carl T. Haas, for spending a lot of their valuable time guiding me throughout my degree, and for supporting me and being enthusiastic, encouraging, patient, and for making everything possible. I would like to thank my thesis readers Professor Clark Dickerson and Professor John McPhee. I would like to thank my colleague Karim Alrayes for his cooperation with me in the technical part of the study. Also I would like to thank my friends in Waterloo for their encouragement and support and for making me feel like at home.

Special thanks to my friends Talal Aldobaiki, Ahmed Aljarba, and Abdulrahman Alsuhaibani for their continuing support and encouragement.

Last but not the least I thank my parents and my brothers and sisters; Sarah, Sulaiman, Haya, Saud, Monirah, Turki, Adel, and Khaled for their love and support. Without them I could not do it.

Dedication

إهداء

الى من سهر الليالي وتعب وبذل الغالي والنفيس لكي اصل الى ما انا عليه، الى اللذان لا يرجوان مني شيئاً مقابل ما يقدماه لي دوماً : أبي و أمي اتمنى ان اكون قد افرحتكم ولو قليلاً و انت تكونوا فخورين بوصولي الى هذه الدرجه. بدون جهودكم، ما كان لشئ ان يتحقق.

شكراً لكم

To those who stayed up late and spent everything possible to make me what I am now, to them who do not expect me to give them anything in return for what they are giving me, my parents. I hope I made you happy and proud of what I accomplished. Without you nothing would have been possible.

Thank you

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background and need

The number of industry, workers, tools, and equipment has increased lately, thus work-related injuries have increased as well. This increase in the number of injuries is affecting both workers' health and industrial economy. Therefore, many organizations [1-3] have tried to limit the number of injuries among workers by: establishing guidelines and manuals on how to perform specific tasks [4], funding research to investigate injury causes and effects, organizing seminars and workshops to educate workers and employers, and writing reports about different tasks and their environmental and human impact.

However, these methods, manuals, guidelines, and studies, did not lead to a complete solution for the problem of interest. Furthermore, some of the manuals, guidelines, and the suggested methods to solve the problems, are not practical in the field for many reasons such as: work space constraints, worker level of education, psychological barriers, and the technical difficulty in monitoring and verification of worker compliance.

Therefore, the field is in need for a solution that can monitor the causes of the problem without: interfering with the surroundings in the work field, causing any delay in the work flow, resulting in negative psychological feedback on the worker, or adding cost to the task budget. At the same time the new method has to be accurate and reliable as it will be one of the most important aspects to decide whether the worker is subjected to an injury.

1.2 Scope and objectives

Proceeding from the growing number of work-related injuries and the unnecessary losses to workers' health, well being and to the economy, this research aims to enable simple, cheap, and reliable solutions to an important class of workers injuries, namely Shoulder injury. This solution will undergo testing to validate its performance and to investigate its feasibility as a tool to solve the problem at hand.

Shoulder injury, is one of the major injuries that affect a worker during his/her work lifetime. Recent statistics collected by U.S Department of labor [5], show that 6.9% of all injuries among workers in 2008 affected the shoulder. We postulate that most of these injuries are cumulative in nature and that managing the workers' exposure to the risk factors associated with these injuries can decrease this high percentage significantly.

Health organizations suggest that workers and work places follow ergonomic policies and guidelines custom-designed for each job to decrease the risk factors leading to injury instead of treating it. Many studies investigated the causes and factors that affect the human body during work; this field is often called Work-related Musculoskeletal Disorders (WMSDs).

In this research, work-related shoulder injury will be analyzed in details with a view to finding ways and means to decrease its frequency by managing exposure to its risk factors. Our proposed approach is to develop simple, cheap, and reliable methods to apply ergonomic guidelines to reduce exposure to those risk factors. This solution will help workers follow ergonomic guidelines as well as assure employers and their insurers that their workers are following those, thereby decreasing the prevalence of shoulder injuries.

1.3 Methodology

In this section, we discuss the methods we adopted to: identify risk factors of shoulder injury, identify methods and tools to assist in implementing protocols to reduce exposure to those factors, and implement those methods and tools.

Sets of solutions were examined for feasibility, cost, size, accuracy, and the ease of use. In addition to these considerations, the following criteria were key factor in deciding what type of solution to use:

- The solution must not suffer from the surrounding interference in the work field.
- The solution must not give the worker a negative psychological feeling that he is being monitored.
- The solution must not be an obstacle preventing the worker from doing his/her tasks in a regular way.

The final step is to validate the results obtained using the proposed solution in our lab against a well known motion tracking method (Vicon). Using the proposed solution, health organizations' guidelines to help prevent shoulder injury can be achieved and monitored. Accordingly lowering the risk of some tasks will have its effect on both health and economic aspects.

1.4 Thesis structure

This thesis is consisted of three chapters followed by a conclusion, recommendations, and future work as follows:

- First is a literature review to investigate the most relevant causes of shoulder injury among workers reported in the literature.
- Second is external musculoskeletal joint angle sensor which includes a detailed explanation for the proposed solution and on how the sensor is working. This section discusses the concept that this sensor applies, how the sensor is working with other components in the circuit and what are the devices being used, in addition to the sensor, to complete the required mission.
- Third is sensor reliability: this chapter is dedicated to validate the output of the proposed sensor in addition to verifying the sensor precision compared to motion capture techniques. Then, through analyzing the data and comparing it to other results in the literature, a conclusion can be made and the solution can be verified to work properly.
- Discussion, conclusion, and future work include the outcomes of this research and recommends future work to enhance the results of this study.

Chapter 2

Literature Review

This chapter reviews and analyzes available literature on shoulder injury among construction workers to better understand its underlying factors and ways and means to mitigate it. Specifically, it will

1. Explain shoulder anatomy and terminology required to better understand the shoulder injury problem.
2. Discuss and explaining the different arm posture combinations.
3. Discuss the various aspects of shoulder injury and the effects they have on workers and the work field.

2.1 Shoulder anatomy

Shoulder refers to the synergetic muscles, tendons, ligaments and joints that work together allowing full motion of the upper arm around the shoulder joint. Figure 1 shows the shoulder anatomy. It consists of three bones: the scapula, clavicle, and humerus. Musculature of the shoulder includes rotator cuff muscles, deltoid, trapezius, serratus anterior, subclavius.

Shoulder pain is any kind of pain that contribute in eliminating the ability of a person to perform the full arm motion (flexion and extension in sagittal plane, abduction and adduction in frontal plane, and internal-external rotation in transverse plane) [6]. Shoulder pain can be classified into four basic categories as follows [6]:

- Shoulder impingement.
- Tendonitis/Bursitis.

- Instability.
- Arthritis.

Shoulder impingement usually occurs as a result of scapula pressure with arm elevation. Rotator cuff is the group of muscles and tendons that assist to stabilize and move the shoulder. Shoulder impingement pain is caused by the inflammation of the top surface of the rotator cuff (bursitis), the rotator cuff itself (tendonitis), or partial tear of the rotator cuff [6].

Bursitis is the inflammation of bursa, which is a cavity that filled with fluid located around the joint to diminish the friction as the joint moves. Bursitis usually occurs in accordance with rotator cuff tendonitis [6].

Tendonitis is the inflammation of the tendon, which is a cord linking a muscle to a bone or any other tissue. Causes for tendonitis over the long term exposure are: (a) Overuse of the muscle e.g. ball throwing or work-related activities such as working in an awkward posture, this kind of tendonitis referred as acute tendonitis. (b) Degenerative or repetitive disease due to age and the improper use of muscles, this kind of tendonitis referred as chronic tendonitis. (c) Splitting and tearing of tendons because of acute injury [6].

Instability, joints in the normal status allows the body part to do a full motion e.g. extension/flexion of the knee, Instability is when the joint is moving out of its normal range. This case often called joint (name of the joint) dislocation [6].

Arthritis, is the inflammation of joints, shoulder arthritis involves wear and tear. Swelling, pain, and stiffness are common symptoms of arthritis [6].

Figure 1 Shoulder anatomy

[http://orthopedics.about.com/cs/shouldersurgery/a/dislocation.htm]

2.2 Shoulder joint motion

Any motion of the upper arm relative to the torso occurs around the glenohumeral joint. Shoulder joint is often modeled as a ball and socket joint. It allows the 3 dimensional movement of the upper arm relative to the torso. Upper arm motion is described in three different planes as shown in figure 2. Shoulder postures that result from upper arm motion relative to torso is described in this section; a brief clarification of terms used to describe each posture will help visualizing the situation.

Overhead work: It is the situation when a worker performs tasks that require a worker to lift his/her arm above head level.

Mid level work: It is the situation where a worker performs tasks in the height of his/her middle chest with arm to torso angle of 45 – 90 degree.

Waist level work: It is the situation where a worker performs tasks in the height of his/her waist level with arm to torso angle of less than 45 degree.

Awkward posture: It is the situations that working while on these postures are more likely to cause injuries to worker's shoulder.

All previous postures are relative to the worker himself, there is no standard to these heights, meaning there is no fixed arm height for each posture. Most of the health organizations' guidelines that aimed to decrease the risk of having MSDs suggested redesigning the work place to be ergonomically safe for the workers. Although these guidelines have proven their efficiency theoretically, in reality inter variability of workers' body types and sizes prevent applying these guidelines through redesigning the workplace. Meaning it is normal to find workers with different age, race, sex, shape, and health condition working in the same place doing the same job. Therefore, a work place cannot be ergonomically redesigned based on a standard height or size.

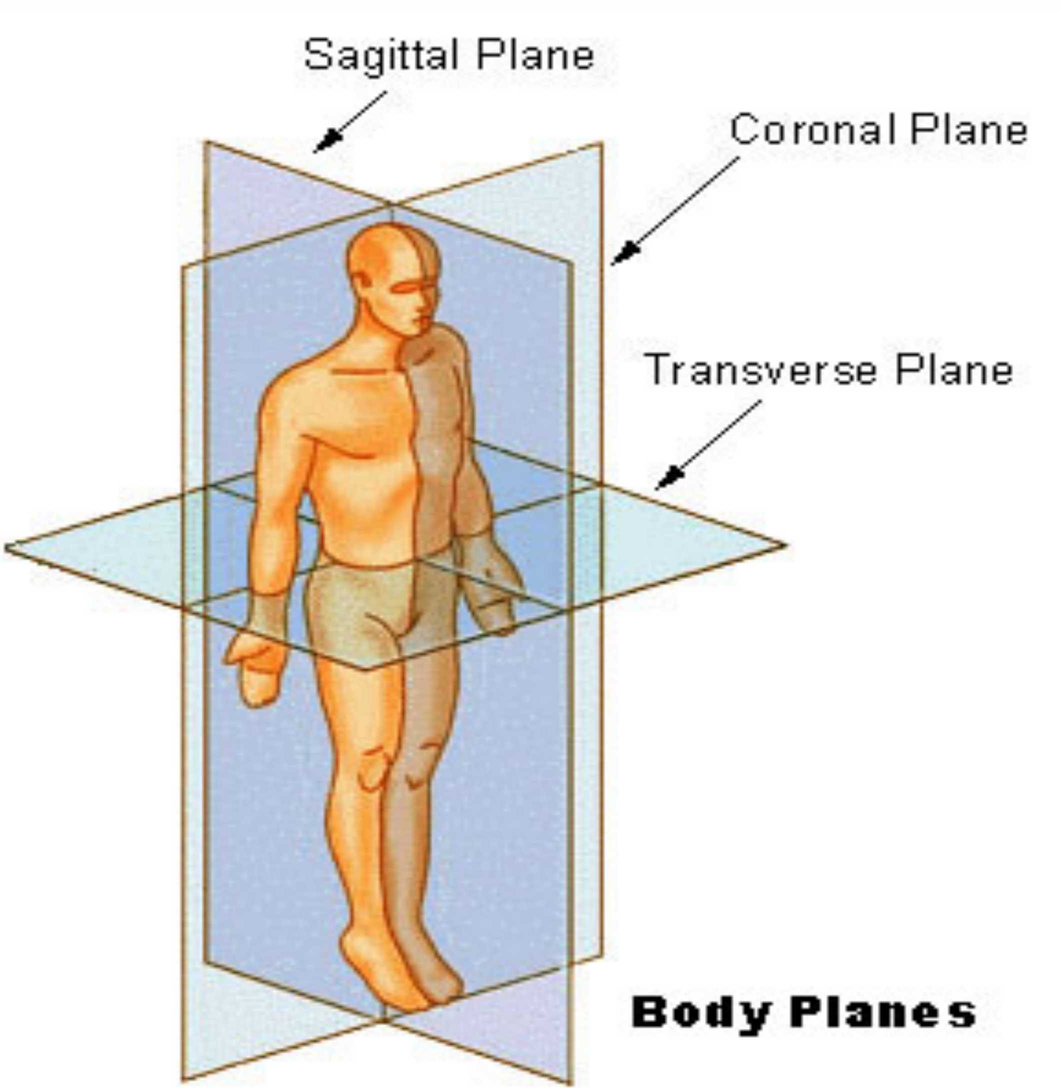

Figure 2 Body planes

The challenge that the diversity of workers' anthropometrical parameters is bringing forward requires a method that can help applying health organizations' guidelines. The required method should be applicable, practical and efficient.

2.3 Musculoskeletal disorders (MSDs)

Public health organizations use different terms to describe Musculoskeletal Disorders (MSDs), such as repetitive stress injury (RSI), repetitive stress disorders (RSD), repetitive motion injury (RMI), repetitive motion disorder (RMD), overuse syndrome, and cumulative trauma disorder (CTD). Fortunately, all health organizations agree on the major aspects of MSDs. In the following we present some of the definitions.

The National Institute of Occupational Safety and Health (NIOSH) defines MSDs as "injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and disorders of the nerves, tendons, muscles and supporting structures of the upper and lower limbs, neck, and lower back that are caused, precipitated or exacerbated by sudden exertion or prolonged exposure to physical factors such as repetition, force, vibration, or awkward posture. (This definition specifically excludes those conditions such as fractures, contusions, abrasions, and lacerations resulting from sudden physical contact of the body with external objects.)" [3].

The Institute of Medicine defines MSDs as "disorders of … the low back and upper extremities. With regard to the upper extremities, these includes rotator cuff injuries (lateral and medial),epicondylitis, carpal tunnel syndrome, tendinitis, tenosynovitis of the hand and wrist (including De Quervain'sstenosing tenosynovitis, trigger finger, and others) and a variety of nonspecific wrist complaints, syndromes, and regional discomforts lacking clinical specificity. With regard to the low back, there are many disabling syndromes that occur in the absence of defined radiographic abnormalities or commonly occur in the presence of unrelated radiographic abnormalities. Thus, the most common syndrome is nonspecific backache. Other disorders of interest include back pain and sciatica due to displacement and degeneration of lumbar inter-vertebral discs with radiculopathy, spondylolysis, and spondylolisthesis, and spinal stenosis” [7].

The Bureau of Labor Statistics (BLS) defines MSDs to “include cases where the nature of the injury is sprains; strains; tears; back pain; hurt back; soreness; pain; hurt; except the back; carpal tunnel syndrome; hernia; or musculoskeletal system and connective tissue diseases and disorders, when the event or exposure leading to the injury or illness is bodily reaction/bending, climbing, crawling, reaching, twisting, overexertion, or repetition. Cases of Raynaud's phenomenon, tarsal tunnel syndrome, and herniated spinal discs are not included.” [1].

The National Research Council (NRC) defines MSDs as “musculoskeletal conditions that may be caused by (non-accidental) physical work activities include disorders of inflammation, degeneration, and physiological disruption of muscles, tendons, ligaments, nerves, synovia, and cartilage involving limbs and trunk. These entities are included in categories 353-355, 722-724, and 726-729 of the International Classification of Diseases (ICD-9)” [8].

All definitions agree that MSDs cover all disorders that affect muscles, tendons, ligaments and the bony structures of the human body. The definitions disagree on whether to restrict MSDs to those disorders resulting from performance of repeated motion patterns over extended periods of time only or to also include disorders arising due to accidents.

2.4 Work related musculoskeletal disorders (WMSDs)

Work-related MSD is a subdivision of MSD that refers to any MSD caused by work circumstances, tasks, or activities. In this thesis, shoulder WMSDs are studied and a monitoring system is designed to help decrease the prevalence of shoulder injuries among construction workers. Assessing the full impact of shoulder injury requires examination at two levels: How often do workers sustain shoulder injuries? and what are the consequences of these injuries?

According to the U.S Department of Labor statics, sprain-strain injuries were 39% of all nonfatal injuries and illnesses requiring days out of work in 2008. Out of these sprain-strain injuries 11.7% were shoulder injuries [5].Of all sprain-strain injuries,44.8% were due to overexertion, 11.1% were due to falling on the same level, and 25.8% were due to other causes including injuries from body movements such as reaching, twisting, bending, or slipping. These statistics indicate that over 70% of sprain-strain injuries were WMSDs under the expanded definition (including accidents).

MSDs constituted 29.44% of all injuries requiring days out of work in 2008. This percentage reflects roughly the danger level MSDs pose to workers in all work fields. Figure 3 shows the median days out of work for each affected body part. At a median of 20 days out of work per injury, shoulder injuries are ranked as the MSDs requiring the longest period away from work to heal. This finding is particularly interesting since it runs against the conventional wisdom that back injuries are a more important factor in the work place. It shows that shoulder disorders are more of an acute injury than back disorders.

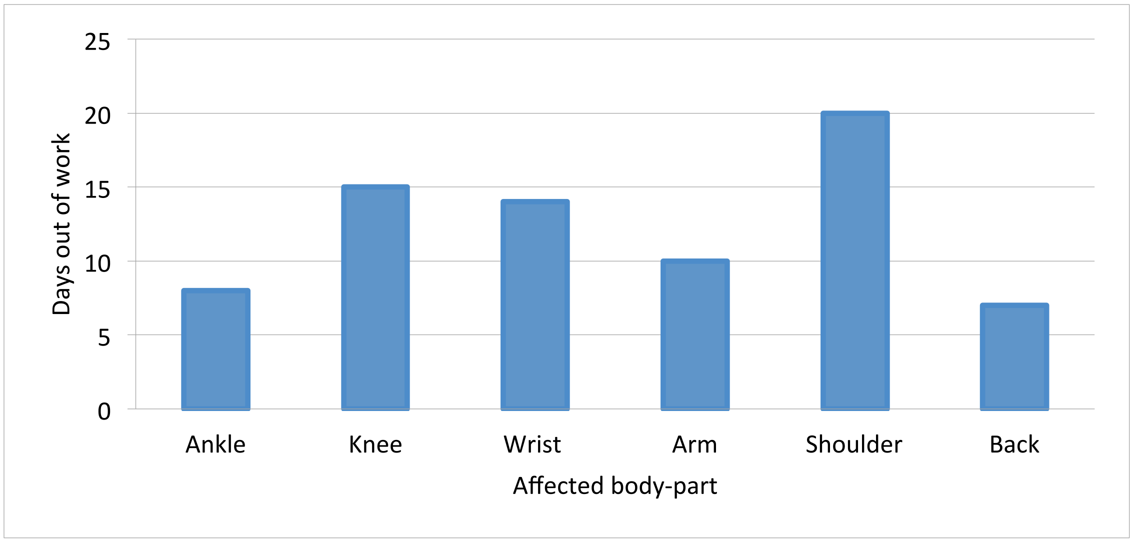

Figure 3 Median days out of work for each injured body part

While shoulder injuries required a median of 20 days to heal, 42.3% of all shoulder injuries required more than 30 days out of work as shown in figure 4.The extended period of days away from work required for shoulder injury healing (over a month) has several implications:

- It indicates significant wear and tear on worker musculoskeletal system.
- It precipitates a need to replace the worker temporarily leading to:
  1. Training of a new worker.
  2. Significant treatment expenses for the injured worker.
  3. Delays to work schedule.

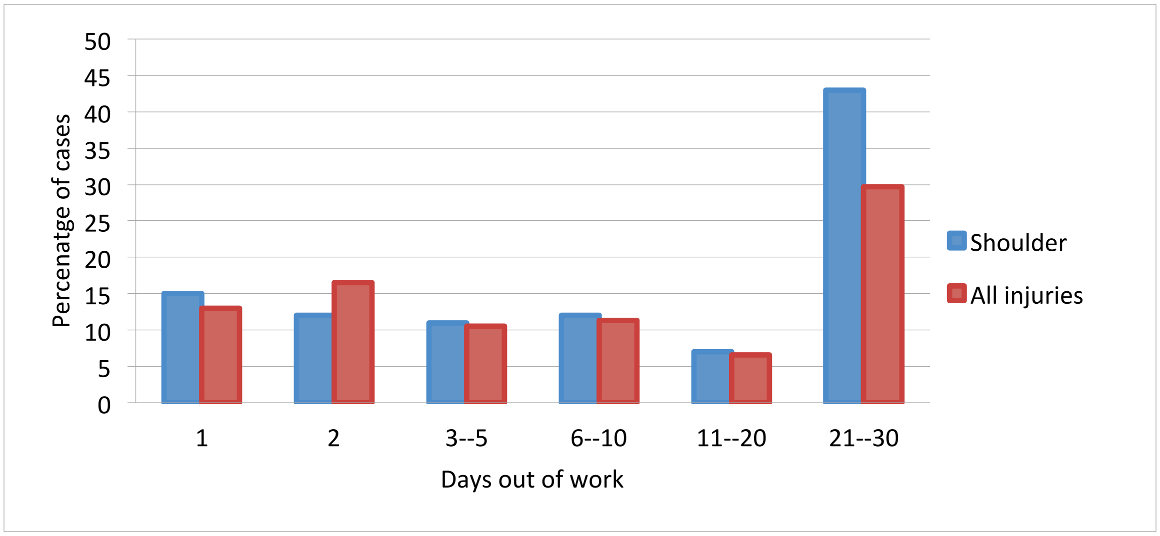

Figure 4 Percentage of days out of work due to shoulder injuries (blue bars) and all MSDs (red bars) across all occupations

Figure 5 shows the median days spent out of work per nonfatal injury and illness for all job categories [5]. Construction and trade, transportation and utilities led the job categories in days out of work required for the injury to heal.

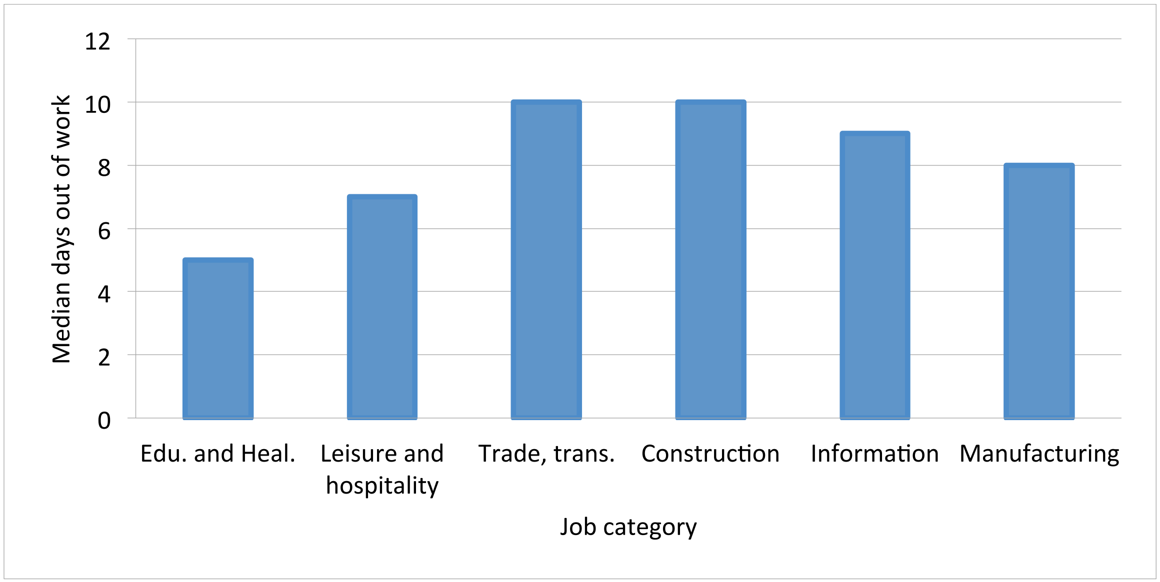

Figure 5 Median of days spent out of work due to injury and illness for all job categories

The percentage days out of work required for all nonfatal injuries and illnesses in the construction industry is shown in figure 6. Only 30% of all injuries in construction required more than 30 days of treatment compared to 43% of shoulder injuries. These statistics indicate that shoulder injuries are not only debilitating compared to injuries to other body parts but also that they are particularly serious in the construction industry.

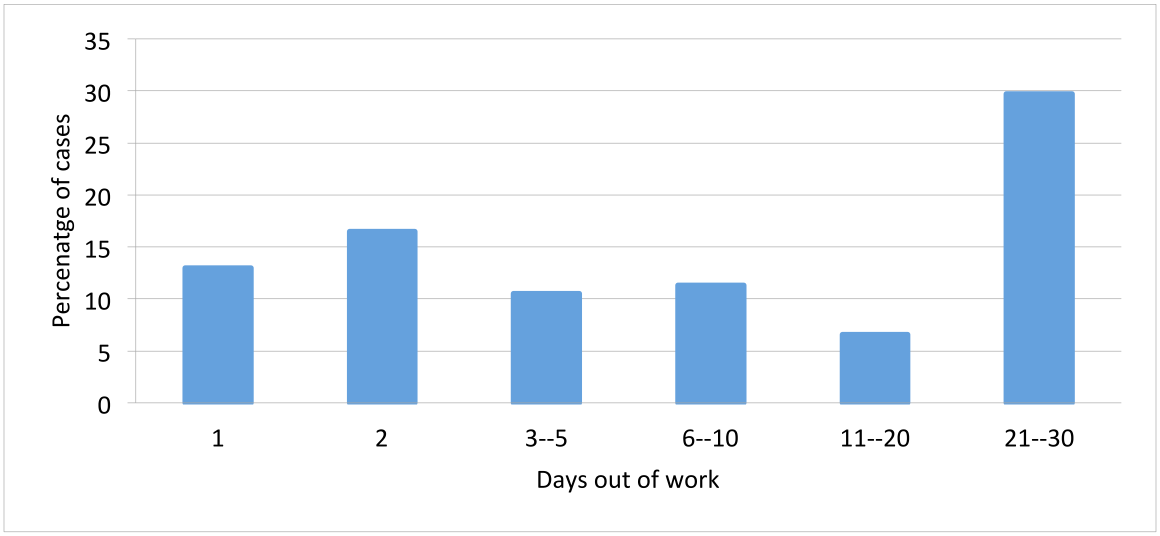

Figure 6 Distribution of days spent out of work for all injuries and illnesses in construction

The BLS [5] defines a quantitative measure for the likelihood of a specific injury in a certain occupation as the incidence rate (IR).The IR is calculated using the formula [5]:

$$IR = \left[\frac{N}{EH}\right] x \ 2x10^7 \qquad \textbf{(2.1)}$$

where:

N = number of reported injuries and illnesses.

EH = total work hours of all employees during the calendar year.

$2x10^7$ = work hours for 10,000 full-time equivalent workers (calculated at 40 hours per week and 50 weeks per year).

The IR for sprain, strain, and tear injuries (which include MSDs) in construction was the highest at 43.8 per 10,000 full time employee among all occupations. Figure 7 shows the relationship between the IR of shoulder injuries and time spent on the job for construction workers. The IR increases progressively in the first five years of work before tapering off for workers who have spent more than five years on the job. We hypothesize that the increase in shoulder injury during the first five years of work indicates that shoulder WMSDs occur due to cumulative processes. On the other hand, the drop in IR over the long-term (more than five years) indicates that workers who adapted successfully to the proper technique for above head-level work were able to decrease the risk factors for shoulder injury resulting in a reduced IR for experienced workers (beyond five years).

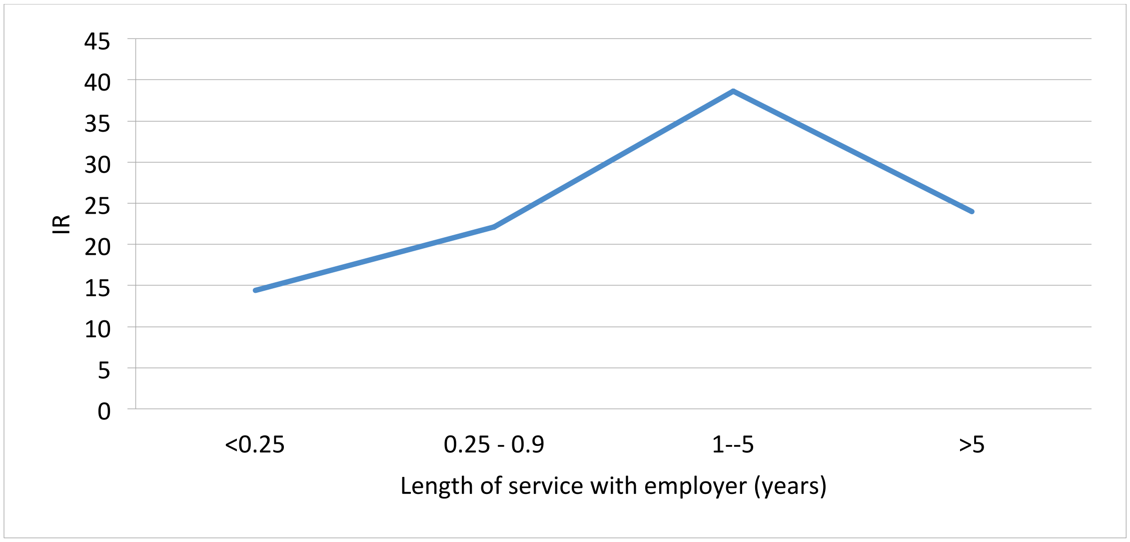

Figure 7 IR with respect to length of employment

BLS data reported above is consistent with the finding of Frost et al. [9] who reported that the prevalence of upper extremity injuries among workers in jobs that require overhead work rose within their first 5 - 8 years on the job, decreased, then rose again after spending more than 25 years on the job. These results indicate that upper extremity injuries are cumulative in nature, rather than individualistic or discrete incidents, since they appear as an outbreak after 5-8 years on the job. Workers who acquire proper technique to reduce the risk factors of work-related musculoskeletal stress do not suffer that outbreak accounting for the drop in those injuries beyond 5-8 years on the job. The increase in the prevalence of shoulder injury beyond 25 years on the job is quite alarming, since it indicates that at this point in the worker's life-time they accumulate enough risk factors to drive a second outbreak of shoulder injuries for experienced workers who have, presumably, adopted ergonomically acceptable work techniques. These results may indicate that short and long-term prevalence of upper extremity WMSDs among construction workers is due to the accumulation of risk factors over time for inexperienced (short-term) and experienced (long-term) workers who spend significant time working in overhead postures.

The previous statistical data reveal an interesting relationship between shoulder WMSDs and job category. Thus, a detailed analysis of the literature on WMSDs will follow to further understand the relationship between shoulder WMSDs and work type.

2.5 Risk factors contributing in the development of WMSDs

There is a lack of consensus in the literature on the risk factors contributing to MSDs. This section will investigate the risk factors cited in the literature for shoulder WMSDs.

Four risk factors are listed for shoulder WMSDs in the NIOSH review of evidence of potential risk factors for shoulder injury [10]:

- Highly repetitive work [11-17]: workers are subjected to tasks requiring performance of the same movement repeatedly, for example 10 times per minute, such as butchers, meat packers, cashiers, and assembly line workers.
- Vibration [18]: workers are subjected to tools that vibrate during operation. Vibration of the tool is then transmitted through the worker's body while performing his/her task.
- Sustained awkward shoulder-posture [11, 13, 14, 19]: workers perform tasks while they are in ergonomically awkward postures for extended periods of time. Some of these studies reported that arm elevation is related to shoulder tendonitis (inflammation of shoulder tendons).
- Forceful work [15, 18, 20]: worker perform tasks requiring exertion of significant amounts of force (pulling, pushing, lifting, compressing) to complete it.

We note that while almost all tasks in construction industry require the exertion of significant amounts of force, only some of these tasks require the assumption of awkward shoulder postures, expose workers to vibration, or involve repetitive work.

Considering the level of significance of the relationship between those factors and shoulder WMSDs, NIOSH review [10] concluded that available evidence did not justify considering highly repetitive work and vibration as major causes for shoulder WMSDs. Furthermore, the prevalence of shoulder WMSDs was low in occupations where forceful work was not combined with awkward postures. Since construction-related occupations involve forceful work, sustained awkward postures are more likely to cause shoulder WMSDs than in other industries. In fact, awkward posture alone can be safely used as an indicator of exposure to risk factors for WMSDs among construction workers. Therefore, this study focuses on finding solutions to manage workers' exposure to awkward postures in construction fields to maintain it within pre-established safe limits.

2.6 Awkward shoulder posture

Researchers have not settled yet on a threshold for ergonomically awkward postures or a method to describe it. Different studies have found various combinations of awkward shoulder-postures. The challenge is to decide what is an awkward shoulder-posture as far as the purposes of this thesis are concerned?

An awkward shoulder-posture is a shoulder posture that can cause MSDs if maintained by a person for enough time and accumulated over a work life-time. The angle between the torso and the upper arm is the standard indicator of an awkward shoulder-posture.

Herberts et al. [20] reported that the deltoid muscle showed clear evidence of activity increase when the arm was elevated from 45 - 90 degrees relative to torso. Furthermore, supraspinatus muscle had a considerable amount of activity when elevated to an angle more than 45 degrees. In other words, this study indicates that elevating the upper arm to angle of 45 - 90 degrees requires substantial amounts of muscle activity, which would suggest that elevating the arm to an angle of 45 - 90 degrees in any direction is an awkward shoulder-posture. Therefore, for a worker to be ergonomically safe he/she has to work with their arm either below 45 degrees or above 90 degrees of flexion/abduction.

Levitz et al. [21] reported that as the space between the acromion and humeral head decreases, the pressure on supraspinatus tendon increases. Further, elevating the arm to an angle of 60 – 120 degrees relative to torso showed the greatest pressure on supraspinatus tendon. This suggests that elevating the arm to an angle of 60 – 120 degrees in any direction is an awkward posture, because it narrows the space between acromion and humeral head to the smallest limit consequently increasing the pressure on supraspinatus tendon. Therefore, workers would have to keep the arm-torso angle either below 60 degrees or above 120 degrees.

In a study comparing shoulder moment with and without external force, Kim et al.[22] concluded that flexing/abducting the arm more than 90 degrees is more likely to cause shoulder injury than flexing/abducting the arm below 90 degrees. This finding would suggest that elevating the arm more than 90 degrees in any direction is an awkward shoulder-posture that will eventually lead to shoulder MSD. Consequently, a worker has to decrease the amount of time spent working above 90 degree of arm flexion/abduction to decrease the risk factors for shoulder WMSDs. Likewise, Svendsen et al. [23] found a relationship between supraspinatus and shoulder pain with workers performing tasks above 90 degrees of arm elevation.

The following aspects were taken into consideration to set a threshold for ergonomically awkward shoulder-posture:

- The strength of evidence.
- The ability of workers to perform tasks efficiently while avoiding awkward postures.

Three combinations of upper arm-torso angle were considered in this analysis:

1. More than 45 degrees is awkward.
2. 60-120 degrees is awkward.
3. More than 90 degrees is awkward.

In terms of strength of the evidence all three definitions were supported by strong evidence.

- The first definition [20] is based on biomechanical and epidemiological studies.
- The second definition [21] is based on pathological studies of localized muscle fatigue.
- The third definition [22] is based on the use of biomechanical models to estimate the forces and moments in the shoulder joint from experimental joint motion data.

Because all three options for an ergonomically awkward shoulder-posture were backed by evidence, the second criterion was used to set the threshold for an ergonomically awkward shoulder-posture. Thus, the practicality of adopting each of these choices was examined. The first definition would require redesign of the tasks or workplaces to allow the worker to perform tasks while maintaining upper arm to torso angle below 45 degrees. This constraint will render some tasks impossible to do such as painting a wall. Moreover, restricting arm elevation up to 45 degrees means that the worker's hand will be at his/her waist level. Thus, workers will tend to bend their back to perform tasks lowering productivity posing risks for low back injuries.

The second definition imposes a constraint that keeps the worker upper arm to torso angle outside an awkward posture zone stretching from 60 to 120 degrees. Excluding this envelope almost no beneficial work can be achieved. It would essentially prohibit the worker from performing tasks below 120 degrees because there are almost no tasks that can be effectively performed with arm elevation below 60 degrees. On the other hand, working with the arm above 120 degrees has been shown to be unsafe [22].

Third definition restricts the worker to an arm elevation less than 90 degrees. This solution is the most practical because:

- Most of construction tasks can be performed with an arm below 90 degrees of elevation.
- Where that is not possible, most workplaces can be redesigned to allow workers to perform their tasks while the arm is elevated at angle below 90 degrees.
- Working with an arm below 90 degrees will not affect productivity noticeably.

2.7 The monitoring system for shoulder injury among construction workers

Injury theories [24, 25] hold that injuries occur when tissues are exposed to loads exceeding its tolerance threshold. Injuries are classified based on the exposure time of the tissue to loads into three categories:

- Injuries due to a single load incident in excess of the tissue failure threshold.
- Injuries due to exposure to multiple cycles of sub-failure loads over intermediate time. Tissue tolerance to loads decreases by repeated exposure to sub-failure loads. When the tolerance level eventually drops below the load, it results in tissue injury.
- Injuries due to exposure to sub-failure loads over extended periods of time. Tissue tolerance decreases further by applying sub-failure loads for extended periods. Eventually, it does not require moderate sub-failure loads to cause injury, as in case 2, even small cyclic loads applied over extended time and enough number of cycles will lead to tissue injury.

Researchers [24, 25] suggest that if injury is detected at a micro-level, before the tissue tolerance decreases significantly, and the tissue is allowed to recover for some time, it will not be at risk of injury because the tissue-adaptation phenomenon will increase the tolerance back to its normal limit.

We found in previous sections that construction workers, construction companies, and insurance companies need a practical solution to help decrease shoulder WMSDs prevalence. The obstacles against redesigning the workplace to make it ergonomically safer and the fact that workers develop shoulder injuries even when they try to adopt safety guidelines drive the need to build tracking systems to track and manage workers' exposure to the risk factors of shoulder WMSDs. This study is proposing a solution using a programmable angle sensor to track workers' upper arm motion, store the data, then post-process it to determine whether a worker had exceeded a threshold of time spent in awkward shoulder-postures defined based on best available data.

In fact such data is already available in the literature. For example, Svendsen et al. [23] found that in 3.9% of all supraspinatus and in 18.3% of shoulder pain without disability cases workers were performing 6-9 % of their tasks above 90 degrees of arm elevation. They also found that 5.4% of all supraspinatus cases and 15.3% of all shoulder pain cases without disability were among workers who spent more than two years performing tasks requiring arm elevations above 90 degrees.

Therefore, if weekly or monthly monitoring reports reveal that a worker has performed tasks above 90 degrees elevation for longer than a pre-set safety limit, a decision can be made to either change the worker's task or type of work for a period of time long enough to allow the shoulder to heal from the micro-damages. In this thesis, a monitoring system was designed to measure time spent by workers in an awkward posture as a step towards facilitating decisions on whether the worker is in danger of a shoulder injury by comparing time spent in an awkward posture with published data to decide whether the worker exceeded the threshold of the safe working envelope.

Chapter 3

External Musculoskeletal Joint Angle Sensor

Shoulder injuries among construction workers need a solution that can be used anywhere in the work place to monitor the workers posture continuously. This solution must be:

- Cheap
- Compact
- Easy to use
- Accurate

The solution should not:

- Interfere with the worker in performing his/her tasks.
- Suffer from interference by the surroundings in an un-structured work site.

In this chapter, candidate solutions will be considered against this set of criteria to choose a suitable solution and monitoring system employing that solution will be proposed.

3.1 State of the art

Researchers have used many techniques to track the movement of body parts over the years both off line and on-line. Gyroscopes, accelerometers, motion capture techniques, video analysis, ultrasonic sensors, integrated systems, and magneto-resistive sensors are among those sensors. All of these techniques have advantages and disadvantages that will be discussed briefly in this chapter.

3.1.1 Gyroscopes

Researchers use gyroscopes to obtain the orientation and angular position of body parts in space [26, 27]. Gyroscopes measure the angular velocity of the body part it is attached to. Therefore, gyroscopes are axis dependent sensors that have to be aligned with the axis of rotation to obtain accurate readings.

Gyroscopes are useful for indoor applications, because of their sensitivity; however, they cannot withstand shocks due to falling or other impact events. Also most gyroscopes are hard-wired constraining the user to remain close to a controller and adjusting the user's motion pattern under test. Wireless gyroscopes are available; however, they are expensive and liable to high noise floor and drift over time. Therefore, gyroscopes are not a suitable solution as a sensing element for the motions of a construction worker in the field since the worker must have the freedom to move anywhere on site without worrying about the sensor.

3.1.2 Accelerometers

Accelerometers are used to locate body parts orientation and position [28, 29] both as a stand-alone system as well as in conjunction with other sensors such as gyroscope to form a tracking system. Accelerometers measure the axial acceleration of the body part it is attached to. There are uniaxial, biaxial, and triaxial accelerometers depending on the number of acceleration vector components it can measure.

Acceleration data can be integrated to obtain the velocity and displacement of an object. The disadvantage of accelerometer data is that during the first integration process, to obtain velocity, a constant will be generated and it will appear as drift over time at the next level of integration to obtain displacement. This is a particularly significant shortcoming for monitoring-type measurements since the time-scale involved in this case is quite long. As a result, a very small drift from zero-mean in acceleration data will evolve over time to a very large displacement error. Accelerometers are also sensitive enough that small shocks can damage them. Further, they share the same shortcoming of gyroscopes in being either hard-wired or wireless and liable to interference with their signal in a work environment. Therefore, accelerometers are not a practical choice as a sensing element for the motion of a construction worker.

3.1.3 Motion capture techniques

Motion capture techniques are widely used in biomechanics research to track the movement of body parts. One of the motion capture techniques calls for the use of video cameras to record body parts movement. It involves placing markers on different palpable bony landmarks on the body part then recording markers movements. Researchers can then derive the information needed through post processing software [30].

The output motion data are either two-dimensional or three-dimensional. The accuracy of the data depends on the specifications of the system being used, the number of cameras used, and marker size and type. The advantage of this technique is that it provides the coordinates of each marker at in any point in time. So researchers can, for example, detect the location of all relevant body parts in space at any point in time with excellent resolution. Then, through data analysis one can conclude whether a worker is working within the safe work envelope.

A disadvantage of the motion capture techniques is that it can only be performed in a specially equipped lab in order for the system to identify the markers correctly because the cameras consider any shiny object to be a marker. Moreover, each body segment must be covered with a set of markers to be able to track it with respect to other segments or an inertial coordinate system. A complicating factor is the fact that each marker has to be detected by at least 3 cameras all the time to be able to reproduce its coordinates in space. These factors combine to require preoccupying the workplace with several expensive cameras. Also, during the collection some markers might occlude because of an obstacle or lost line of sight. The capital cost of these systems system is in the order of tens of thousands of dollars. Furthermore, extracting the angular position and angular speed of a body segment from the segment coordinates involves a nontrivial analysis process using Euler angles and transformation matrices.

Therefore, neither two-dimensional nor three-dimensional motion capture systems are practical solutions as sensing elements in a work place because of the variety of places that a worker can work in during a single day and the fact that no construction site can be configured as a motion capture lab. Furthermore, it will require a large number of cameras to detect all the markers placed on a body segment at all times because materials, tools, and other workers in the field will block various cameras' line of sight at various times.

3.1.4 Video analysis

Using a video camera researchers record a session of a task or a job of interest then analyze it afterwards to extract kinematic data, such as body posture, joint angles, and segment's location. Each camera can detect one plane such as sagittal plane.

The drawback of this technique is that although it does not require a preset lab, the camera has to be able to record subject movement all the time. In a study to evaluate the ergonomic risk factors for lower extremities [31], some of the video data collected were not evaluated because of missing head frames, due to the anonymity of the participant, and/or the video line of sight was blocked by tools in the workstation.

Therefore, video analysis is not a suitable choice for the sensing element in the musculoskeletal joint angle sensor. Mainly because of the line of sight constraint which is hard to satisfy in a worksite.

3.1.5 Ultrasonic techniques

Ultrasonic techniques have been used for objects tracking over the years [32]. Ultrasonic techniques involve firing and receiving the fired waves. The distance between the transmitter and receiver is calculated from the time elapsed between firing and receiving the wave.

Ultrasonic techniques require knowledge of the paths along which the wave travels to reach the receiver. The transmitted wave takes a conical shape that keeps expanding along the path until it hits a boundary where it is reflected towards the receiver. However, the receiver cannot determine the source of the detected wave.

An ultrasonic transmitter can be placed on the moving body part while the receiver is placed on the fixed body part, for example a transmitter can be placed on the upper arm and a receiver anywhere in the abdomen, then the distance between transmitter and receiver can be calculated. However, the problem will be that there are many positions inside the safe work envelop where the distance travelled by the sound waves will be the same as that travelled for positions outside the safe work envelop. For instance, assuming the worker is performing a task below 90 degrees of upper arm to torsos flexion and he/she moves his/her arm laterally or medially from a neutral position, the distance measured by the receiver will at some points exceed that recorded for an unsafe position of more than 90 degrees of flexion and a neutral arm position. Therefore, ultrasonic devices are not a practical choice for the sensing element required in this study.

3.1.6 Integrated systems

Many researchers have used multisensory systems to track motion. Integrated systems mean the use of hybrid sensing technologies or massive sensor arrays to sense the phenomena of interest. Movement suits and Inertial Measurement Units (IMUs) are examples of integrated systems.

Zhu and Zhou [33] used a combination of triaxial gyroscopes, accelerometers, and magnetometers to track human body motion. Movement suits and IMUs also have been used in the movie industry to capture the motion patterns of characters in three-dimensional animation movies. However, these techniques are expensive, hard to implement, and need complex algorithms and circuits. These techniques do not appear suitable as a sensing element in the musculoskeletal joint angle sensor because of their size, complexity, and cost.

3.1.7 Magneto-resistive sensors

Magneto-resistive sensors use the change in the orientation of magnetic field flux-lines to detect the angle of rotation of the magnet over time. Magneto-resistive sensors are used in the field of mechanics. It has been used to count the rotations of bearing system over time in the field of computer vision to calculate the angle between a truck and a trailer as part of a system to monitor the surrounding of a truck-trailer combination [34]; the idea is consisted of two main parts, one is the magnetic field source and the other is sensing part. Sensing part was used as a fixed frame and the magnetic field source was a moving frame. The magneto-resistive sensors showed practicality in this application. Giant Magneto resistance (GMR) sensors are used as contactless angular position measurement devices [35]. Anisotropic Magneto resistive sensors (AMR) are used to measure the absolute angular position and to obtain the direction of magnetic field in field of automotive design [36].

In this thesis, a system was developed using the AMR to measure the upper arm to torso angle for construction workers in occupations that require significant amount of overhead work, such as electricians, painters, and carpenters. These occupations require upper arm to torso angles that are primarily in the sagittal plane. Thus, the monitoring system will measure the upper arm to torso angle in 2 Dimensions. The monitoring system will need to be expanded to measure the full-three-dimensional shoulder joint angle required for other, more involved, applications.

3.2 The external musculoskeletal joint angle sensor

Two versions of the monitoring system were designed: A tabletop version for preliminary tests and calibration and a portable version to implement the monitoring system on the problem of tracking the upper arm to torso angle of elevation. The tabletop version was assembled on a breadboard and the portable version was assembled on a printed circuit board (PCB). In the portable version, the system was composed of three parts: a magnet which is responsible for generating the magnetic field, a sensing element which is responsible for detecting the change in angle of magnetic flux-lines, and a control unit which contains a Microcontroller Unit (MCU), a power source, and SD card. Data acquired in the portable version is stored on a 2 Giga byte SD card to provide data portability to any computer with an SD card reader.

3.2.1 The KMA200 programmable angle sensor

The KMA200 (Philips semiconductors) programmable angle sensor is used as the sensing element in the monitoring system. The sensor uses the magneto-resistive effect, the property of certain permalloys changing their resistance when exposed to an external magnetic field, to detect the change in the orientation of magnetic field flux-lines as a change in resistance [37]. The sensor measures the change in flux-lines orientation from 0 – 180 degrees. Initially, the magnet must be positioned parallel to the sensing element with its south-pole facing upwards to match the 0 degree direction. As the magnet rotates anti-clockwise, the sensor start measuring angle change until it reaches 180 degrees. If the magnet rotates instead in the clockwise direction, the angles changes in the reverse direction, dropping from 180 degrees towards lower values. If the magnet crosses the 180 degrees line in the counter-clockwise direction, the sensor starts measuring angles from 0 again. Two Wheatstone bridges are used to measure the change in resistance according to the following equation

$$R = R_o + \Delta R_o \cos^2 \alpha \tag{3-1}$$

where R_o and ΔR_o are the base resistance and the coefficient of resistance as a function of flux, respectively, and α is the angle between the magnetic flux-lines and the current [37].

The sensor requires a minimum magnetic field strength of 439.8 Gauss to guarantee a saturated homogenous magnetic field [37]. This is not an electromagnetic wave, this field strength is not harmful for human exposure. The sensor will detect any external magnetic field applied and as the angle of the magnetic field flux-lines change the sensor measures that angle.

The magnet is attached to a body part while the sensor is attached to another body part. Initially, they are placed such that is the magnet's north-south line is parallel to the sensor casing as shown in figure 8. As the body part where the magnet is attached rotates, the sensing element will detect a change in resistance through the Wheatstone bridge. Equation (3-1) can then be used to calculate the angle of rotation of the magnetic field flux-lines and convert it continuously to a voltage based on a dynamic range from 0 to 5V that corresponds to an angle from 0 to 180 degrees.

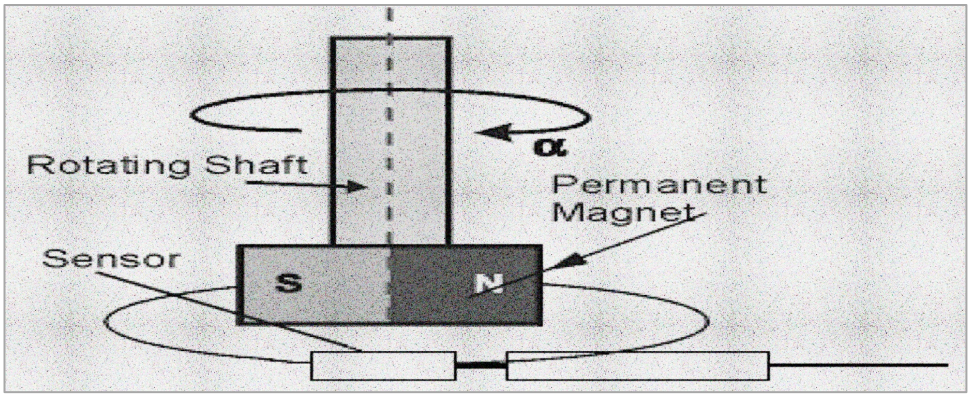

Figure 8 Orientation of magnet source with respect to the sensor [37]

KMA200 sensor provides a choice between analog and digital output signal and among various output modes, such as comparator and inverted modes [37]. It requires an electrical control unit (ECU) to control the data flow in and out of the sensor, 5V power supply, and an external case to carry the system and to protect the system from shocks in the work field.

3.2.2 Data flow

A microcontroller unit (MCU) is used to manage the process of data capture, storage, and transfer. A 40 pin MCU (PIC18F4550) was used for the tabletop version, and 80 pin MCU (PIC18F87J50) for the portable version. In the following, we describe the flow for the portable version of the sensor. Data flow for the tabletop version is quite similar to that of the portable version with the exception of a different pin numbering convention. The sensor layout is illustrated in figure 9 for the portable version and figure 10 for the tabletop version.

After an operator switches the device ON, the MCU sends an “acquire” signal through pin 58 to trigger the sensor to detect available magnetic signals, the sensor then calculates the angle of the magnetic field. The angle measured by the sensor is represented by an analog signal ranging from 0 to 5 V. On its way to the MCU, it enters the potentiometer where its magnitude is adjusted to fit the dynamic range of the A/D converter in the MCU. Specifically, it decreases the dynamic range of the signal to 0 – 3.3 V. The MCU receives the analog signal of the potentiometer through pin 20 and samples it at a rate of 100 kS/s. The sampled signal is digitized in an 8-bit A/D converter, into 1024 discrete bins, and stored temporarily in a buffer stack. The data is held in the buffer until detected through pin 54, then the MCU sets the SD card into read mode through the “control” pins 55 and 34 and starts transferring data to the SD card through pin 45 (or through pins 16 and 17 to the USB and a PC).

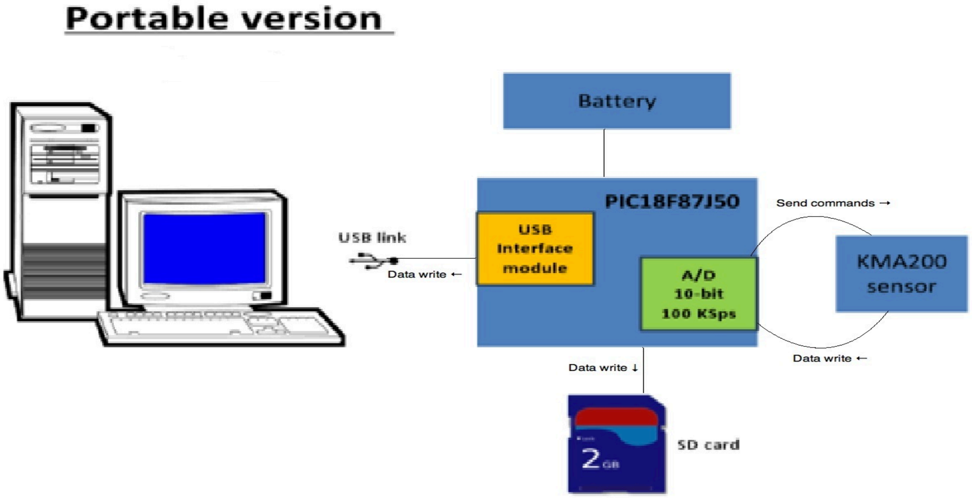

Figure 9 Layout of the portable version

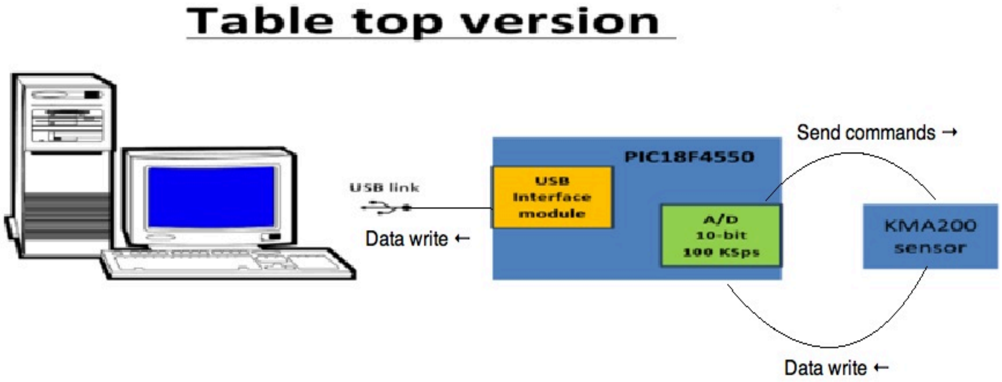

Figure 10 Layout of the tabletop version

A 9V battery is used in conjunction with a voltage regulator to power the system. Power is supplied to the MCU through the positive potential pins 12, 32, 48, and 71 and the ground pins 11, 31, 51, and 70. A 20 MHz crystal is connected to the MCU with the oscillation circuit, between pins 49 and 50, to provide the MCU with a timing circuit. Pin 44 is the timing clock used to synchronize the flow of data in and out of the SD card. Appendix B contains table 1 that lists the pinning information used for this project.

3.2.3 Electrical control unit (ECU)

The tabletop and portable versions use Microchip Company PIC18F4550 and PIC18F87J50 as ECUs, respectively. These MCUs communicate in digital and analog modes to send/receive commands and data. They act as data in/out controllers (Master/slave) and timers for the clock to synchronize sending commands and receiving data. These MCUs have the same voltage requirement as the sensor (5V).

3.2.4 Magnetic field source

The magnetic source used in the system is an off-shelf magnet with an intensity of 5000 Gauss with a mass of 245.8 g. This is one order of magnitude higher than the intensity required to fulfill sensor requirements [37]. The magnet used here is magnetized through the thickness; the north-south poles are across the thickness, which poses a particular challenge to setting the magnetic flux-lines parallel to the sensing element. Figure 11 shows the magnet for the portable version.

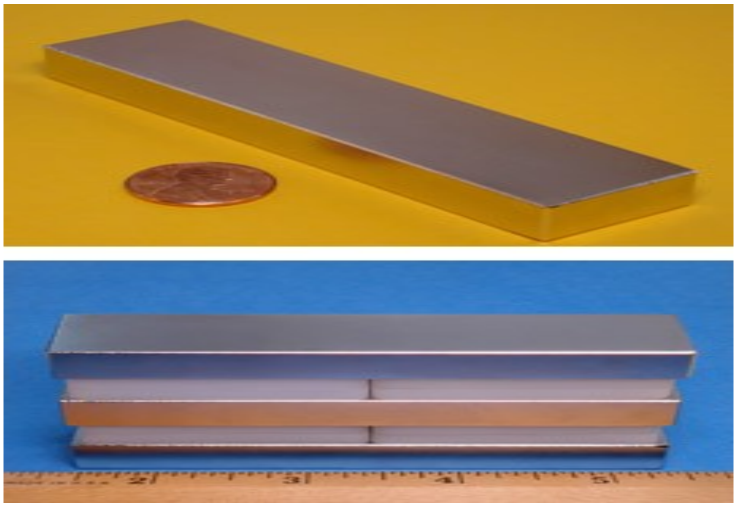

Figure 11 Magnet for portable version use

3.2.5 Power supply

Power requirements for the various components in the sensor system range from 3.3V for the PCB internal voltage to 5V for the sensor and MCUs. Because of wide availability and low cost, a 9V battery was used as the power source for the tabletop and portable versions. A voltage regulator was used to decrease the voltage from 9V to 5V for the sensor and MCUs and a potentiometer to decrease the voltage to 3.3V for the internal voltage of the board.

3.2.6 Universal serial bus (USB) port

Both portable and tabletop versions were designed to enable direct data transfer to a PC through a USB port. A mini USB port was attached to the board to reduce the overall device size. The USB port was used to transfer the data directly to a PC in the tabletop version.

3.3 System integration

The wiring and IC elements in the sensor system are not designed to withstand shocks. Therefore, the sensing element was packaged in a plastic sleeve as shown in figure 12. It was connected to the electric circuit through a single cable so as not to interfere with the worker’s movements and to guard against entanglement. The cable extending from the sensor to the control unit case was taped to the worker's body.

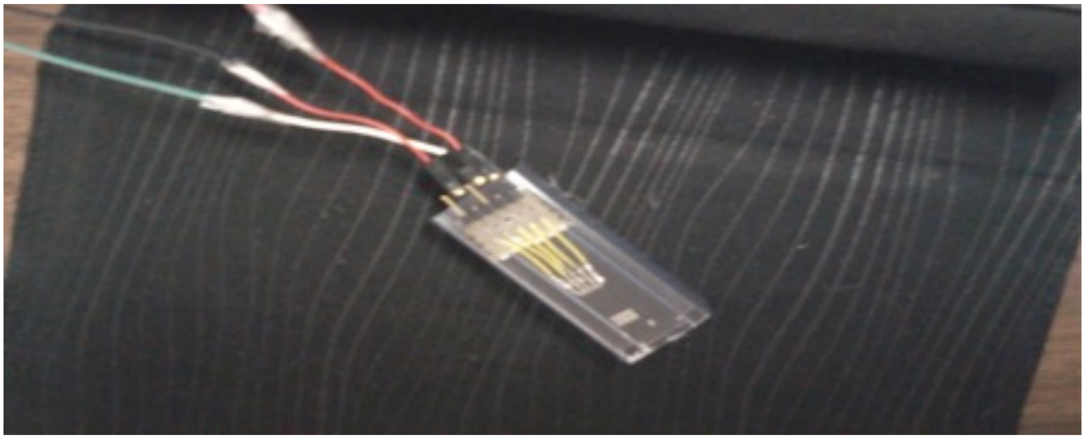

Figure 12 The sensing element inside the plastic sleeve

The magnetic source is mounted on a rubber armband and the assembly is then mounted on the upper arm. The armband is an easy and cheap method to mount the magnet tightly on the upper arm and eliminate movement artifacts. The packaged sensor is also mounted tightly to the axilla using Velcro tape.

The control unit is enclosed in a lightweight 12 x 8 x 6 cm steel box as shown in figure 13. The components of the control unit are shown in figure 14, where the microcontroller marked as (1), the SD card is marked (2), the USB port is marked (3), the power supply is marked (4), and (5) is the steel box. This box is to be mounted on the worker’s belt.

Although this box dimensions are fairly large, it is fairly easy to miniaturize the sensor system once the demonstration portable system reaches mass production.

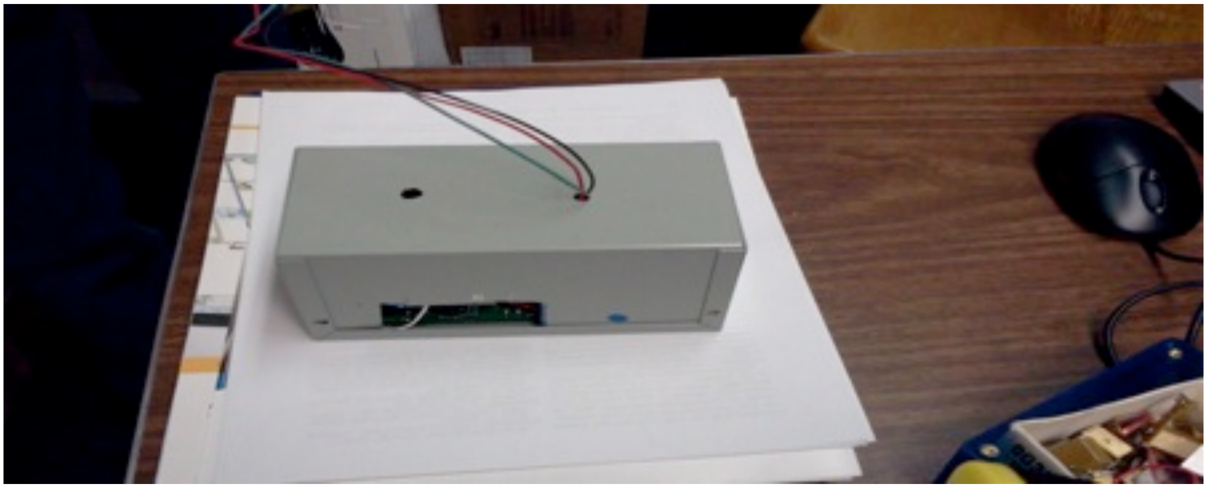

Figure 13 The control unit

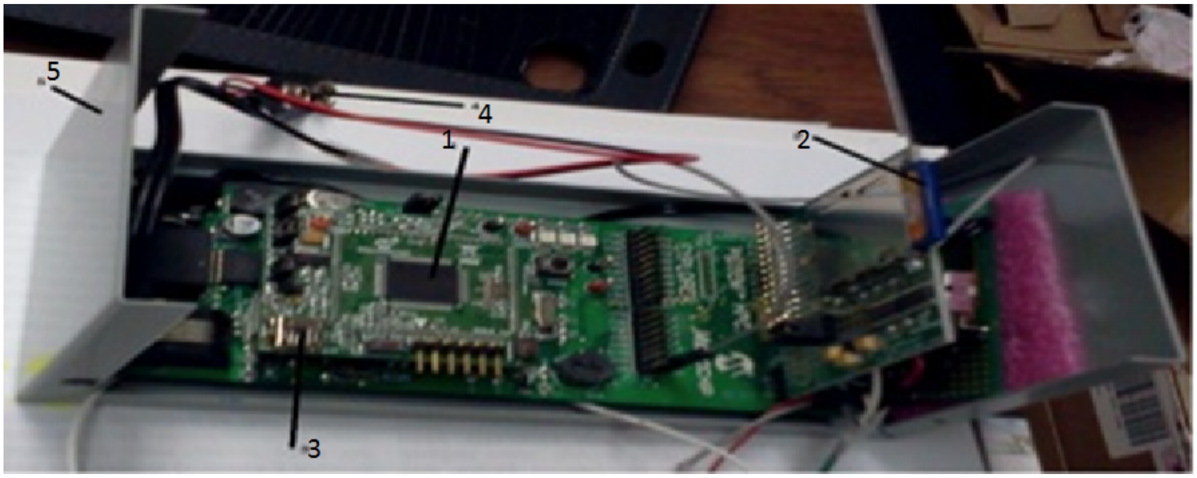

Figure 14 Components inside the control unit

3.4 Operating principle

The goal of the monitoring system is to measure the relative angle between a moving arm frame and a reference torso frame. To achieve that, the sensing element and the magnet are mounted to the axilla and upper arm, respectively. The sensing element is mounted to the axilla rather than the acromion to avoid movement artifacts and to set the magnetic field flux-lines parallel to the sensor. Figure 15 demonstrate the corresponding positions of the sensor and magnet.

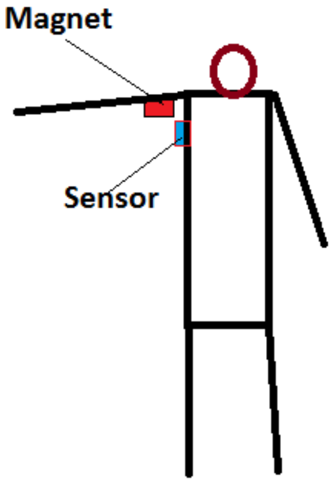

Figure 15 Sensor/ magnet placement on human body

As the upper arm flexes from zero towards 180 degrees the flux-lines rotate with it and the sensor detects the change in angle. The MCU acquires the angle data from the sensor and stores it on the SD card.

3.4.1 Limitations of the sensor system

One limitation of this monitoring system is that the sensing element cannot measure angles more than 180 degrees. This is not a significant limitation for our application since the normal range of flexion for the upper arm relative to torso is less than 180 degrees.

Another limitation is that the system is only capable of measuring movements in one plane (the plane in this case sagittal). To account for this limitation, the target jobs in this thesis are restricted to those occupations, such as electricians and painters, where tasks are mostly performed in the sagittal plane. Therefore, measuring only a 2 dimensional angle is enough to protect the worker.

Chapter 4

Sensor Reliability

In this chapter we report on the calibration and validation of the external musculoskeletal joint angle sensor. The tabletop version of the monitoring system was used to calibrate the sensor. The portable version and a state-of-the-art motion capture system were used to track the upper arm flexion and the results were compared to validate our monitoring system.

4.1 Sensor calibration

The KMA200 angle sensor application note [37] lists the sensor resolution as 0.05^{o}. The tabletop version was used to verify the sensor resolution.

A step motor was used to supply commanded step angular displacements. The motor requires 10V power supply and delivers 1.8^{o} steps. Each step requires 4 different signals; therefore, 4 transistors were connected and controlled using a PIC18F4550 MCU to trigger the motor to perform a step. The control unit was assembled on a breadboard as shown in figure 16. The operating voltage of the MCU is 5V; therefore, a voltage regulator was used to decrease the voltage of AC/DC power supply from 10V to 5V. Figure 16 shows the instrumented step motor where the motor is marked (1), the microcontroller is marked (2), the transistors are marked (3), the AC/DC power source is marked (4), and (5) is the voltage regulator.

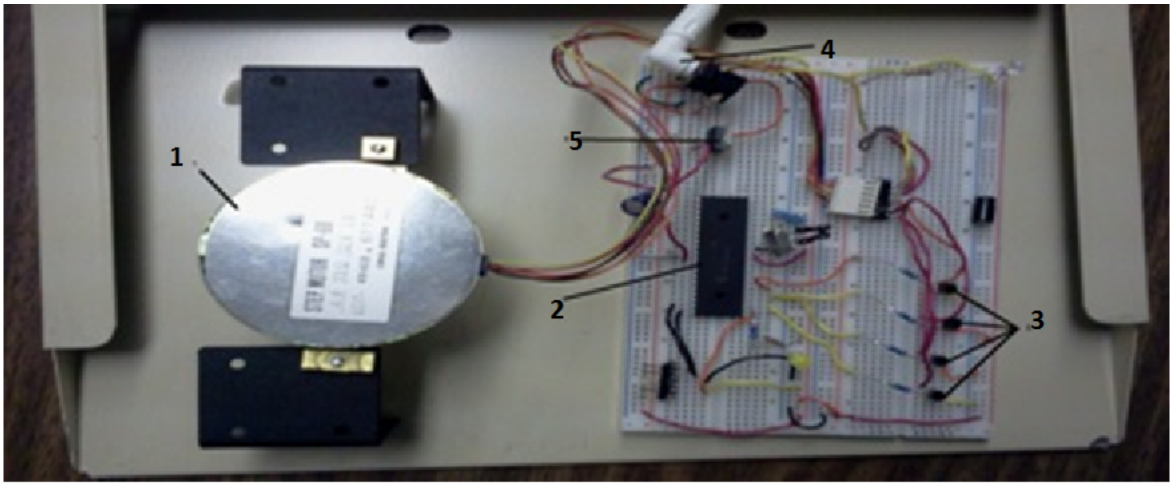

Figure 16 DC step motor and its control unit

A magnet with an intensity of 5000 Gauss was placed on the shaft of the motor. The motor was placed on top of the tabletop system such that the magnetic flux-lines were parallel to the sensor, as shown in figure 16.

The PC was connected to the tabletop sensor through the USB port. The data were temporarily stored in the MCU buffer before sending it to the PC. The experimental setup is shown in figure 17 where the sensing element is marked (1), the magnet is marked (2), the shaft is marked (3), the sensor MCU is marked (4), the USB cable (5) is connected to the PC, and the motor control unit is marked (6).

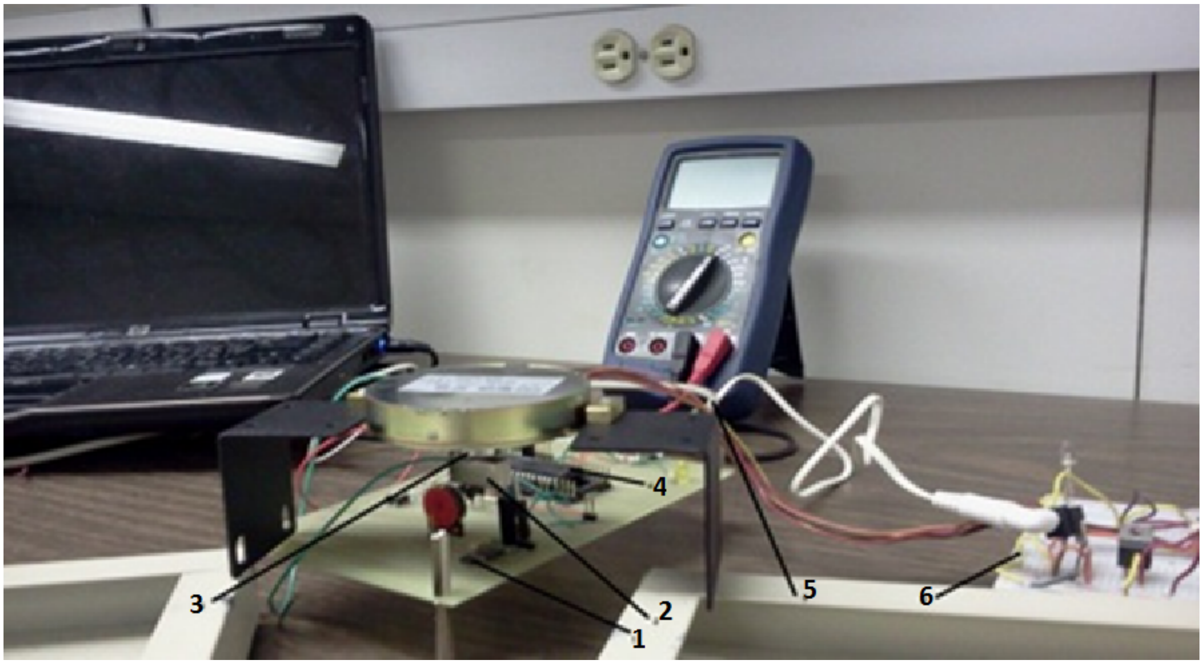

Figure 17 The tabletop experimental setup

A program written in C language was used to interface the PC to the USB port in order to receive and sort the data in a Microsoft Excel file. The motor was commanded to perform 100 steps (180 degrees rotation) in 100 seconds (1 step/s) and the angle was measured using the tabletop sensor and recorded on the PC. The sampling rate was set to 400 samples/s. The time-history of this commanded motion is a staircase curve. The experimental results were in qualitative agreement with the staircase form. Deviations were observed due to motor dynamics, process noise and sensor noise.

Due to motor dynamics, it advances from one step to the next during a finite period of time. For example, as the motor goes from step 3 to step 4, it is neither in step 3 nor in step 4, rather it experiences a transient response during which it overshoots step 4 before settling down to it. The time required for the motor to move from one step and settle down to the next step is called the transient time. Process noise adds uncertainty to the parameters of the transient response. After the motor settles on step 4 in the previous example, the sensor readings vary even though the motor position is stationary at a constant angle. This is called measurement noise, it appears as the deviations from a constant step line in figure 18. We assumed that measurement noise follow a Gaussian distribution, therefore the sensor measurements in the period between settling down to a given step and the start of movement to the next step were averaged to obtain the mean angle for each step. Figure 19 shows the post-processed sensor measurement as the motor performs a 180 degrees rotation.

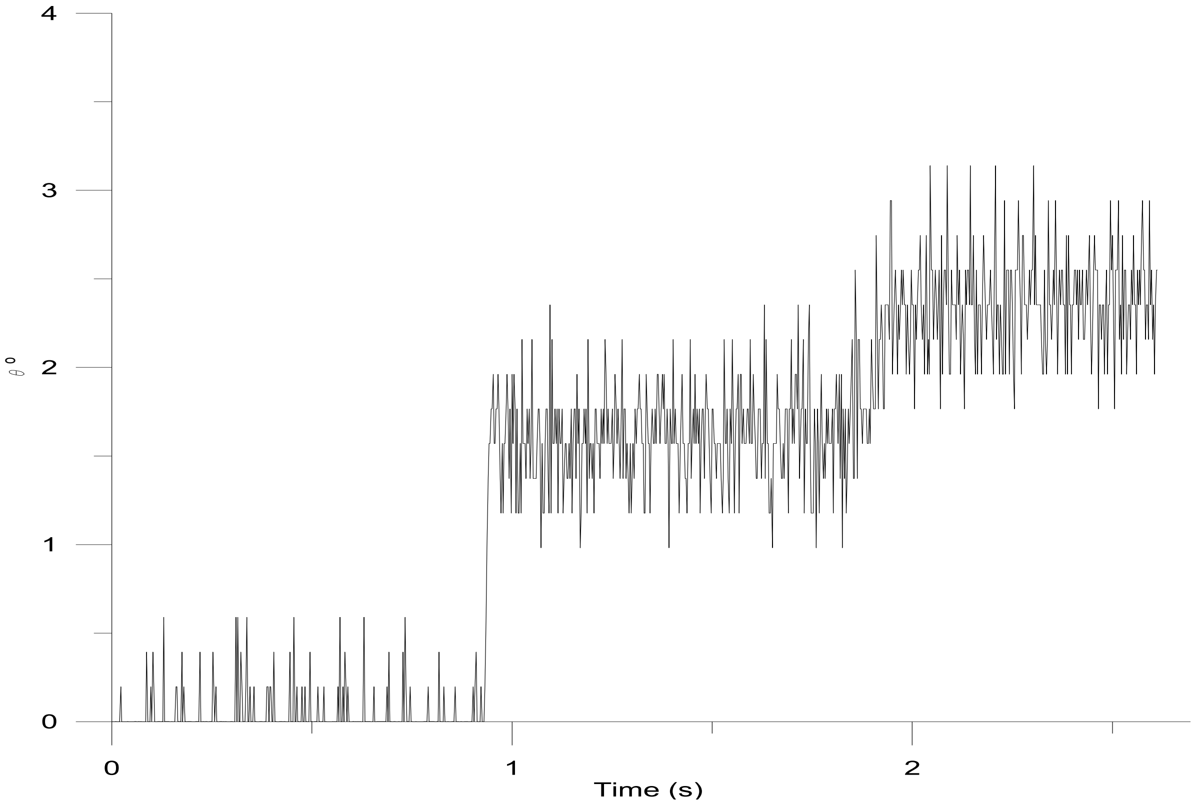

Figure 18 A sample of the raw angle describing the motor angular position obtained using the tabletop version

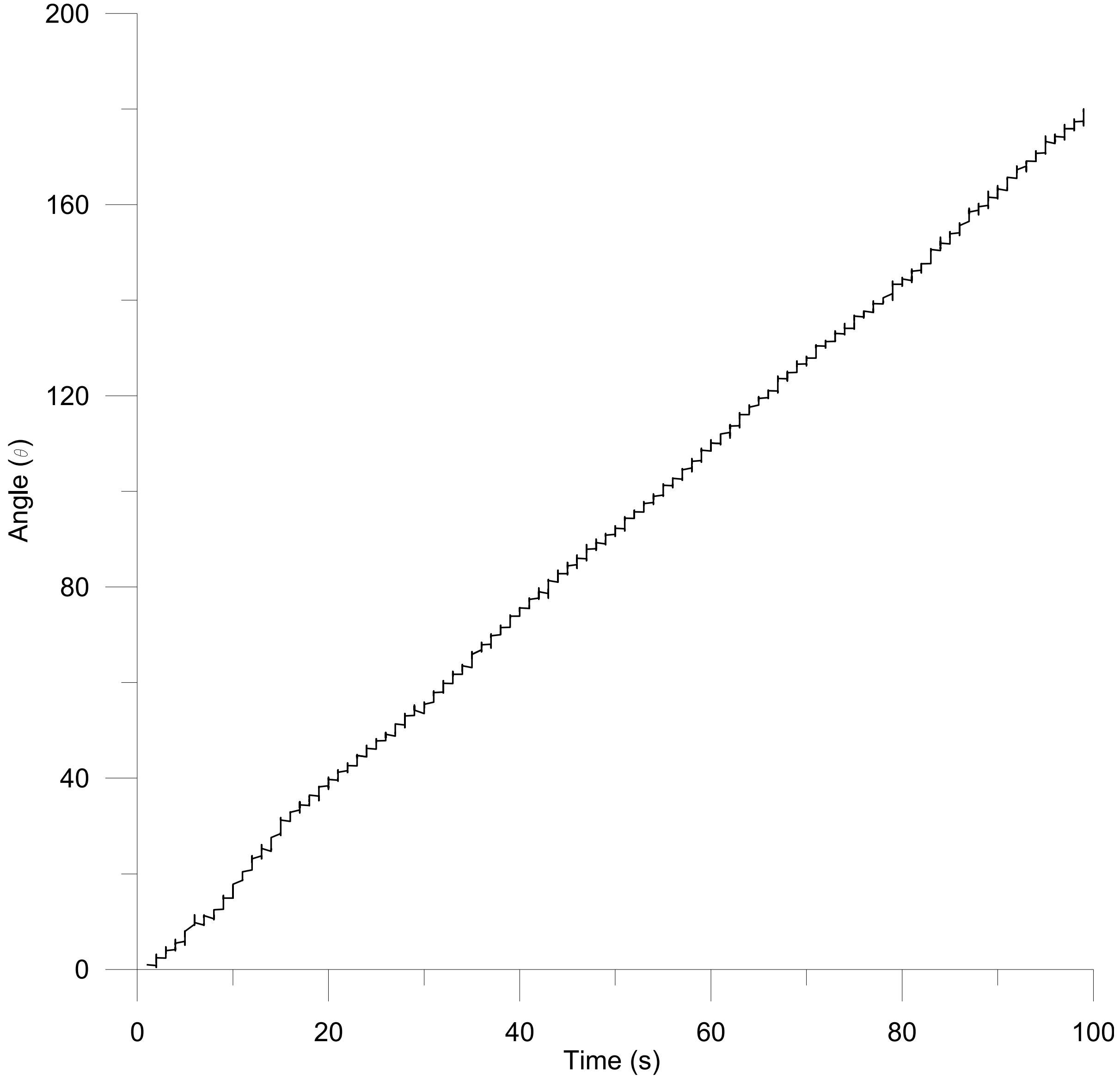

Figure 19 Post-processed angular position of the motor as it performs a 180° rotation obtained using the tabletop version

The standard deviation of the measured angles was found to be in the range 0.12° – 0.34°. This level of precision is one order-of-magnitude larger than the ±0.05° resolution reported in the data sheet [37]. The threshold for dangerous shoulder movements is not very well defined. We estimate that an accuracy of 5^{o} is enough to determine whether a worker is within or outside the safe work envelope. Therefore, we conclude that the KMA200 sensor has a good prospect to satisfy our requirements.

4.2 Sensor validation

To validate the external musculoskeletal joint angle sensor, it was used simultaneously with a commercial motion capture system to measure the angle of elevation of upper arm relative to the torso.

4.2.1 Participants

One healthy right hand-dominant university graduate male student was recruited voluntarily to be part of the study. The participant was 26 years old, 169 centimeters high, and 89 kilograms weight.

4.2.2 Instrumentations

4.2.2.1 Motion capture technique

Right upper arm and shoulder kinematics were measured. Three dimensional right arm movements were tracked using eight Vicon MX20 cameras (Vicon Motion Systems, Oxford, UK) running at 50 Hz. The three dimensional system tracked the location of 19 reflective markers; of the 19 markers, six markers were arranged in two 3-marker clusters, one cluster at the forearm and the other cluster at the upper arm. The remaining 13 markers were placed at the right arm and torso palpable bony landmarks listed in table 1. Figure 20 shows the markers setup on the participant.

Table 1 Markers placement

Marker	Location
1	5th metacarpal phalangeal joint
2	2nd metacarpal phalangeal joint
3	Ulnar styloid
4	Radial styloid
5	Lateral epicondyle
6	Medial epicondyle
7	Acromion
8	C7
9	L5
10	Right posterior superior iliac spine
11	Left posterior superior iliac spine
12	Suprasternal notch
13	Xyphoid process
14	Upper arm cluster 1
15	Upper arm cluster 2
16	Upper arm cluster 3

Marker	Location
17	Forearm cluster 1
18	Forearm cluster 2
19	Forearm cluster 3

Figure 20 Markers placement (right hand)

4.2.2.2 External musculoskeletal joint angle sensor

The portable version of the external musculoskeletal joint angle sensor was used simultaneously to measure the angle of elevation of upper arm relative to the torso. The control unit was placed on the floor, the sensing element was placed on the torso at the axilla, and the magnet was attached using an armband assembly to the upper arm such that the magnet was initially parallel to the sensing element. Figure 21 shows the sensor system placement.

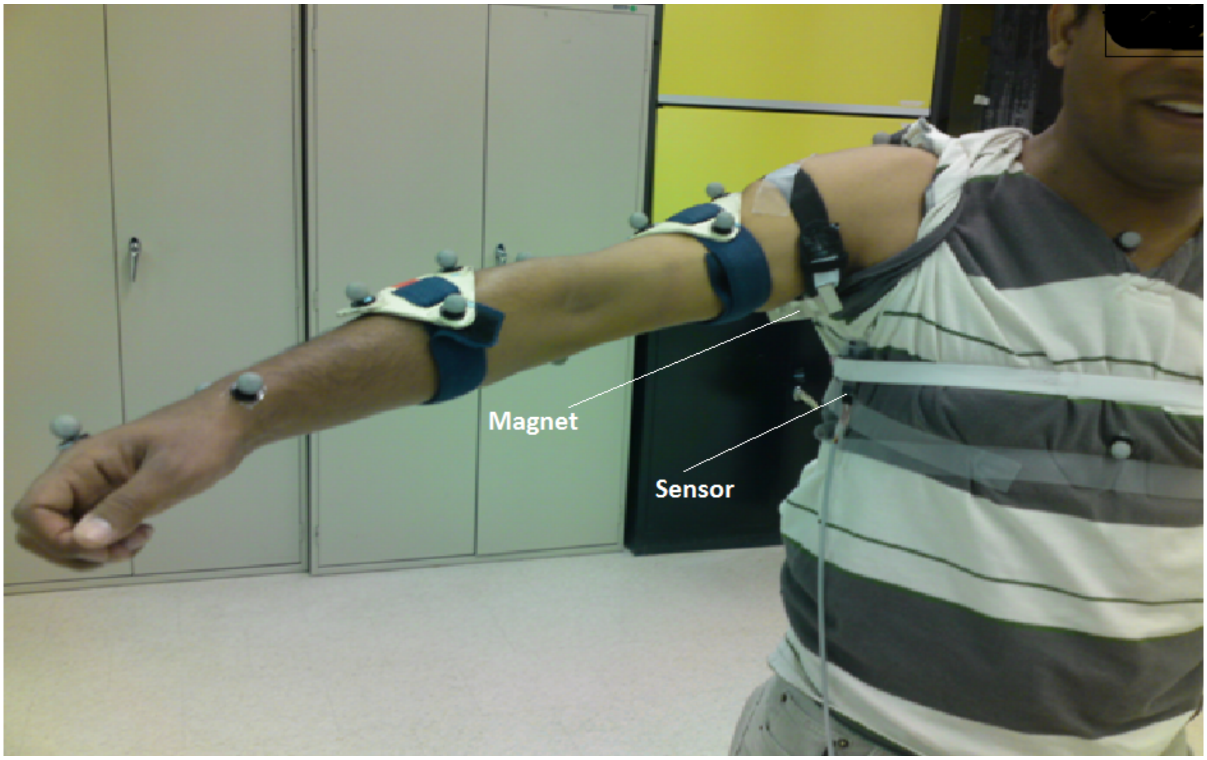

Figure 21 The two sensing methods placed on a subject

4.2.3 Experimental set up

Upon participant arrival to the motion lab, Applied Health Sciences building (BMH 1404), University of Waterloo, the participant was equipped with the set of markers listed in table 2 in addition, the participant was asked to wear the external musculoskeletal joint angle sensor as shown in figure 21.

Before the beginning of a data collection session, the motion capture system was calibrated to set the inertial coordinate system and the collection area using an L shaped wand. After calibration, the participant was asked to sit on a stool located such that it allows the participant to move freely while staying in the first quadrant of the inertial coordinate system (+X, +Y, +Z).

Two operators managed data collection. Operator 1 was responsible for switching the external musculoskeletal joint angle sensor ON and OFF and handling the collected data. Operator 2 was responsible for collecting the Vicon data and processing it afterwards to insure all markers were detected throughout all frames.

4.2.4 Experimental methodology

The experiment was constituted as a feasibility study to identify the behavior of the proposed sensor system in-vivo. First, a pilot run of the external musculoskeletal joint angle sensor was recorded to ensure that it was functional. No data was recorded during the pilot run. Then, the participant was asked to perform five full arm elevations in the sagittal plane starting from an initial position where the arm was at 0 degree flexion to the highest elevation point within his comfortable motion range.

At the beginning and end of each trial, the participant was asked to pause for 1-2 seconds to create a landmark in the time-history that was then used to synchronize the two streams of data recorded using the joint sensor and the Vicon system. After each trial, the participant was allowed to rest while the two operators were saving the trial data. After each trial, operator 1 performed a check on the positions of the sensor and the magnet to whether that they have not shifted their positions during the trial.

4.2.5 Data analysis

The angle between two vectors representing the upper and the torso was calculated from the Vicon data to extract the angle corresponding to that measured using the joint sensor. The data was post-processed to synchronize the two output angles using the pause landmark described above.

4.2.6 Results

A total of 5 trials were conducted. The collected and post-processed results of those trials are described here. Figures 22 to 25 compare the Vicon and sensor measurements obtained in trials 1, 2, 3, and 5, respectively. The results of trial 4 were excluded from the comparison because the magnetic field intensity dropped below threshold during testing resulting in signal loss for the joint sensor.

At the beginning of all trials, figures 22 to 25, the subject was at rest for 1 second, as a result the two signals remained constant with the Vicon reading 34°, 31°, 32° and 25° flexion, respectively, and the joint sensor reading 40° and 0° flexion for the last three trials, respectively. The difference between the initial joint angles measured using the joint sensor in trials 1 is due to a misplacement of the sensing element on the axilla in trial 1. Both signals start rising afterwards with the arm movement until the arm reaches the highest comfortable position at 130°, 118°, 128° and 97° respectively, for the Vicon system and 150°, 200°, 240° and 200° respectively, for the joint sensor before both signals descend back to their starting positions as the arm extends back to zero flexion.

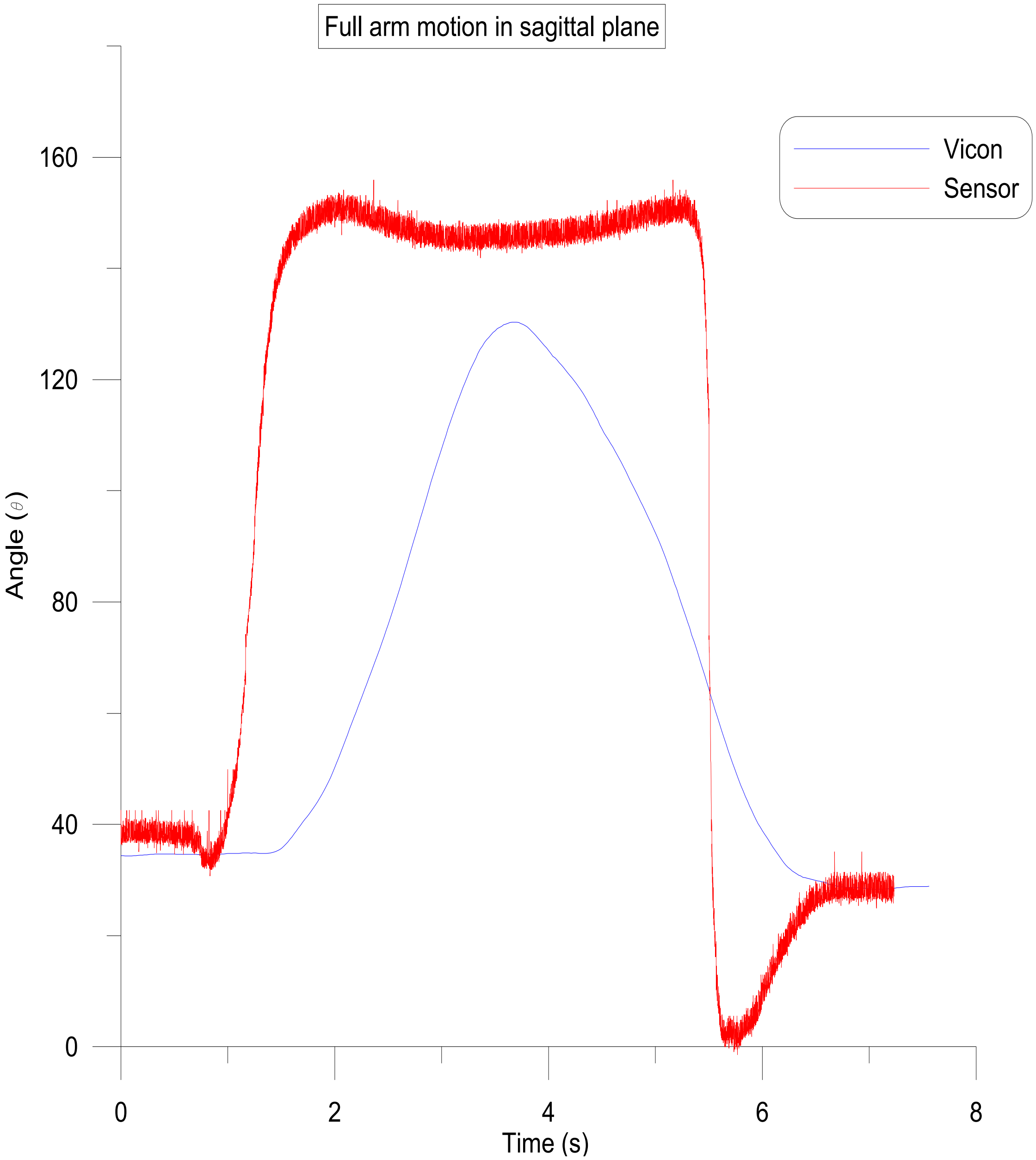

Figure 22 Participant 1 trial 1

We note that the angular speed of the arm motion, the slope of the joint angle, measured using the Vicon was different from that measured using the joint sensor both in ascending and descending.

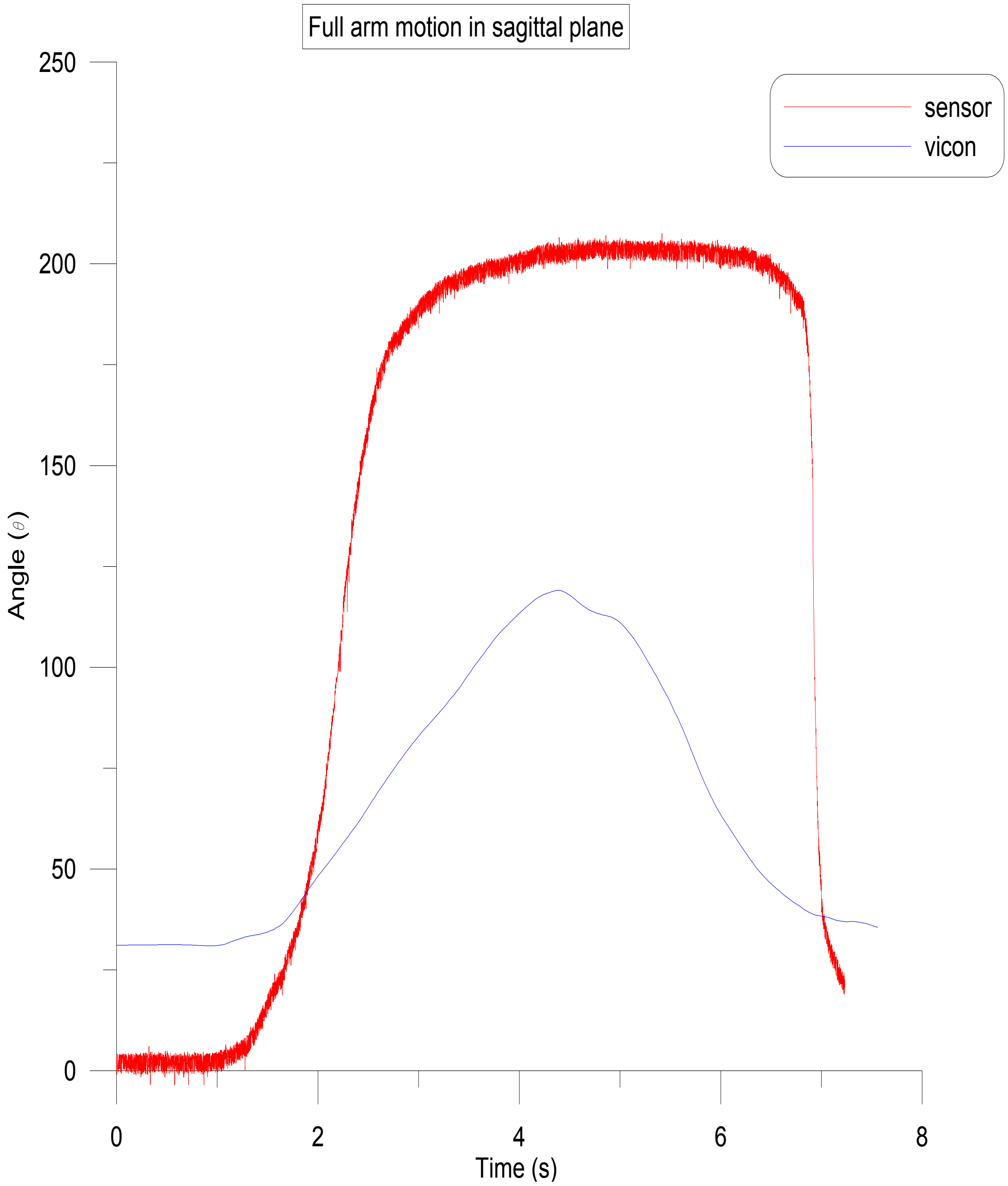

Figure 23 Participant 1 trial 2

Further, while the Vicon measured flexion angle reflects the experimental manoeuvre of a smooth and continuous flexion to a maximum flexion point followed by extension back to the initial position, the angle recorded by the joint sensor saturates to a maximum during the final stage of flexion and the initial stage of extension corresponding to relatively large flexion angles.

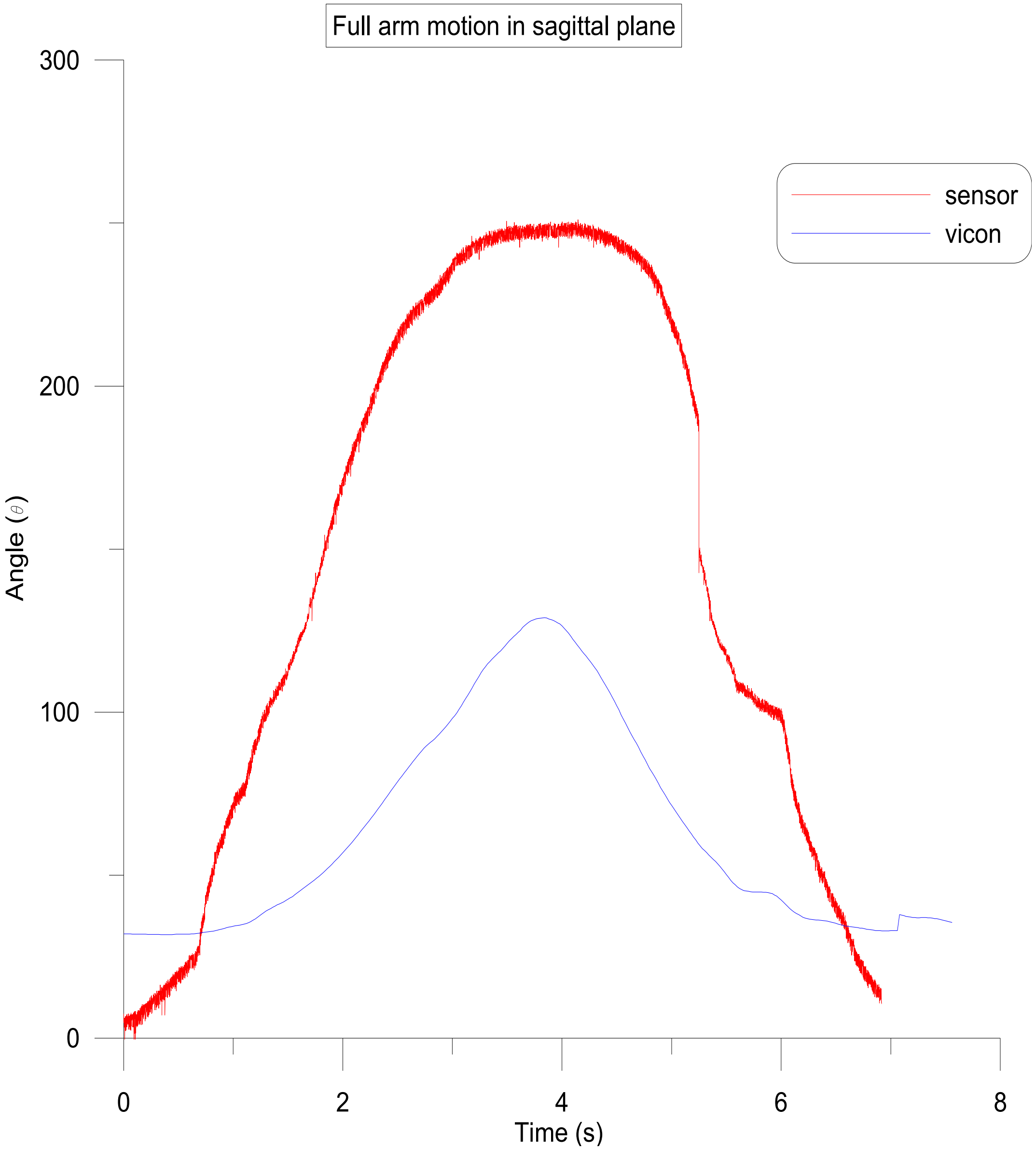

Figure 24 Participant 1 trial 3

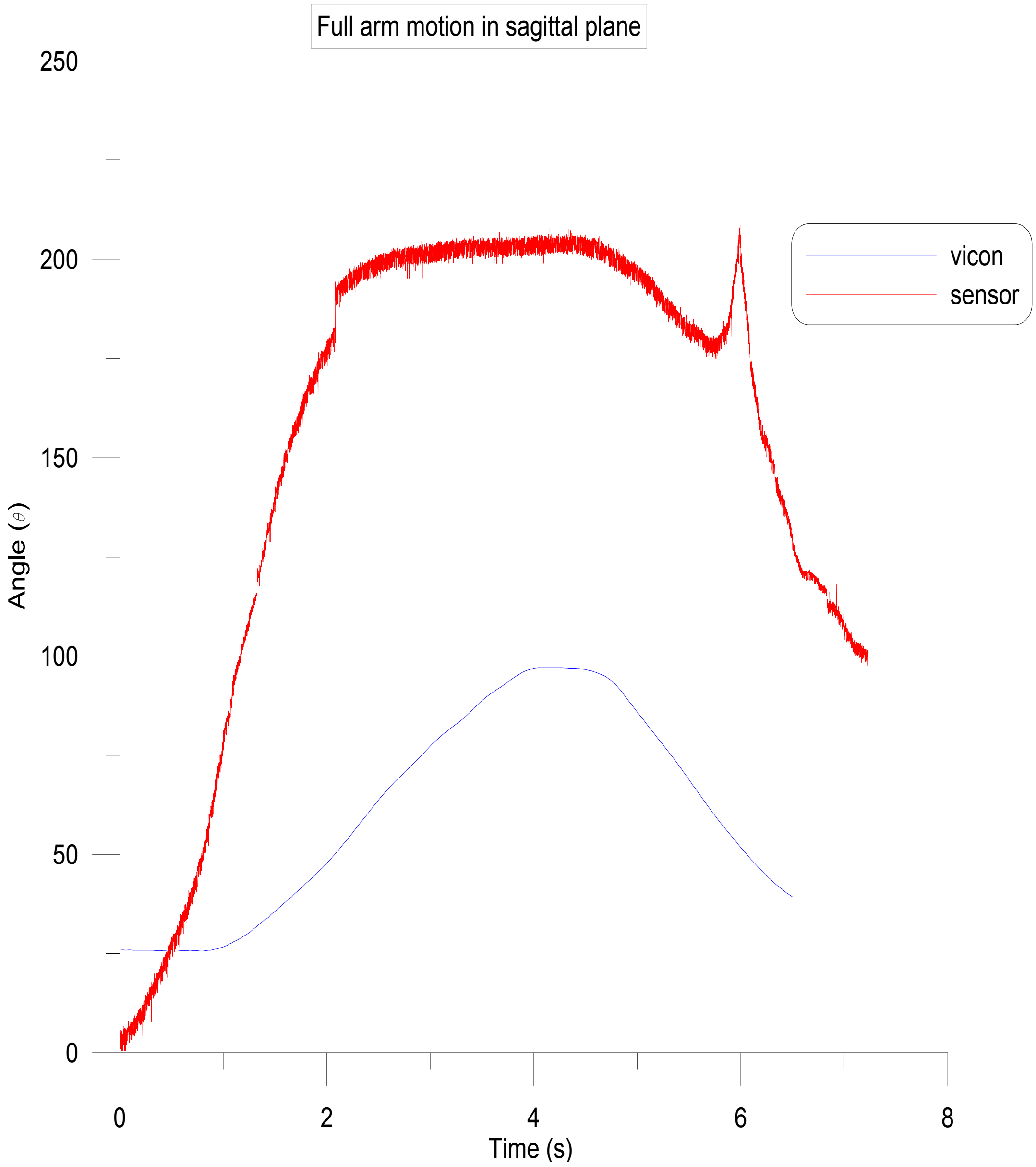

Figure 25 Participant 1 trial 5

Chapter 5

Discussion and Conclusion

In this chapter the results of testing the external musculoskeletal joint angle sensor are discussed and compared to those obtained using the motion capture technique (Vicon).

5.1 Discussion

Figures 22 – 25 showed the output signals measured simultaneously by the external musculoskeletal joint angle sensor and motion capture technique (Vicon) for the same movement where a participant performed full arm flexion in the sagittal plane. In all trials, the initial joint angle measured using the Vicon system is significantly larger than zero flexion ranging from a minimum of 25° in trial 4 to a maximum of 34° in trial 1. The flexion angle calculated using the Vicon system is determined from the formula:

$$\boldsymbol{\theta} = \cos^{-1}\left(\frac{\boldsymbol{A}.\boldsymbol{B}}{|\boldsymbol{AB}|}\right) \qquad \textbf{(5.1)}$$

where **A** and **B** are vectors in the sagittal plane extending from the acromion to middle elbow (representing the upper arm) and from C7 to L5 (representing the torso), respectively, and θ is angle between the two vectors. Comparing the anatomical position of the vectors in equation (5-1) to the anatomical position corresponding to 0 degree flexion, one can predict that the angle θ will be larger than zero as a result of the tissues, for example fat, muscle, and skin, surrounding the upper arm and the torso. The deviation in the angle θ from zero is proportional to the upper arm and torso volumes.

The maximum flexion angle realized during trials was in the range of 100° -130° of flexion. Therefore, the deviation observed throughout motion between the angle measured using the joint sensor and that measured using the Vicon system indicates that the joint sensor consistently overestimates the magnitude of the joint angle. Specifically, the maximum flexion angle recorded by the joint sensor is 80° –120° larger than that recorded by the Vicon system. Further, the difference between the slope of the angular position-time curves measured using the two sensing systems indicates that the joint sensor overestimates the angular speed of the upper arm.

These differences stem from the fact that the sensing element of the joint sensor is designed to measure rotations of the magnetic flux-lines relative to the sensing element. Specifically, the sensing element is designed to measure a change in the orientation of the magnetic flux-lines while the sensing element and the magnetic source are held at the center of rotation. In the experiment we conducted, the magnetic source was rotating and *translating* away from the sensor. We hypothesized that this discrepancy in the sensor placement was responsible for the differences between the measurements recorded by the joint sensor and Vicon system.

To test this hypothesis, an experiment was conducted using the tabletop version of the joint sensor to verify that the sensor overestimates the measured angle when the magnetic source is not placed at the center of rotation. Figure 26 shows a schematic of the experimental setup. A 0–120–0 degrees maneuver to rotate the magnetic source around the sensor was performed; such that:

- In case A, dubbed At CoR, the sensing element and magnetic source were placed at the center of rotation.

- In case B, dubbed Out of CoR, the magnetic source was placed at a distance outside the center of rotation while it rotates around the sensing element.

Figure 27 shows the recorded angle in case A (red line) and case B (blue line).

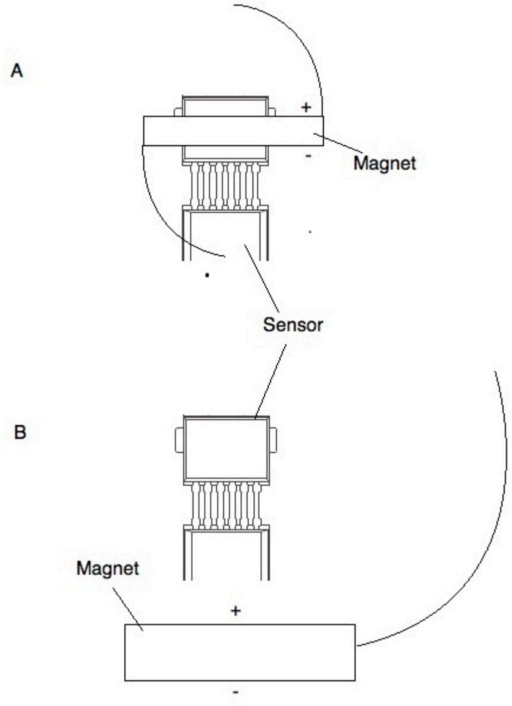

Figure 26 A schematic of two methods of magnetic source rotation

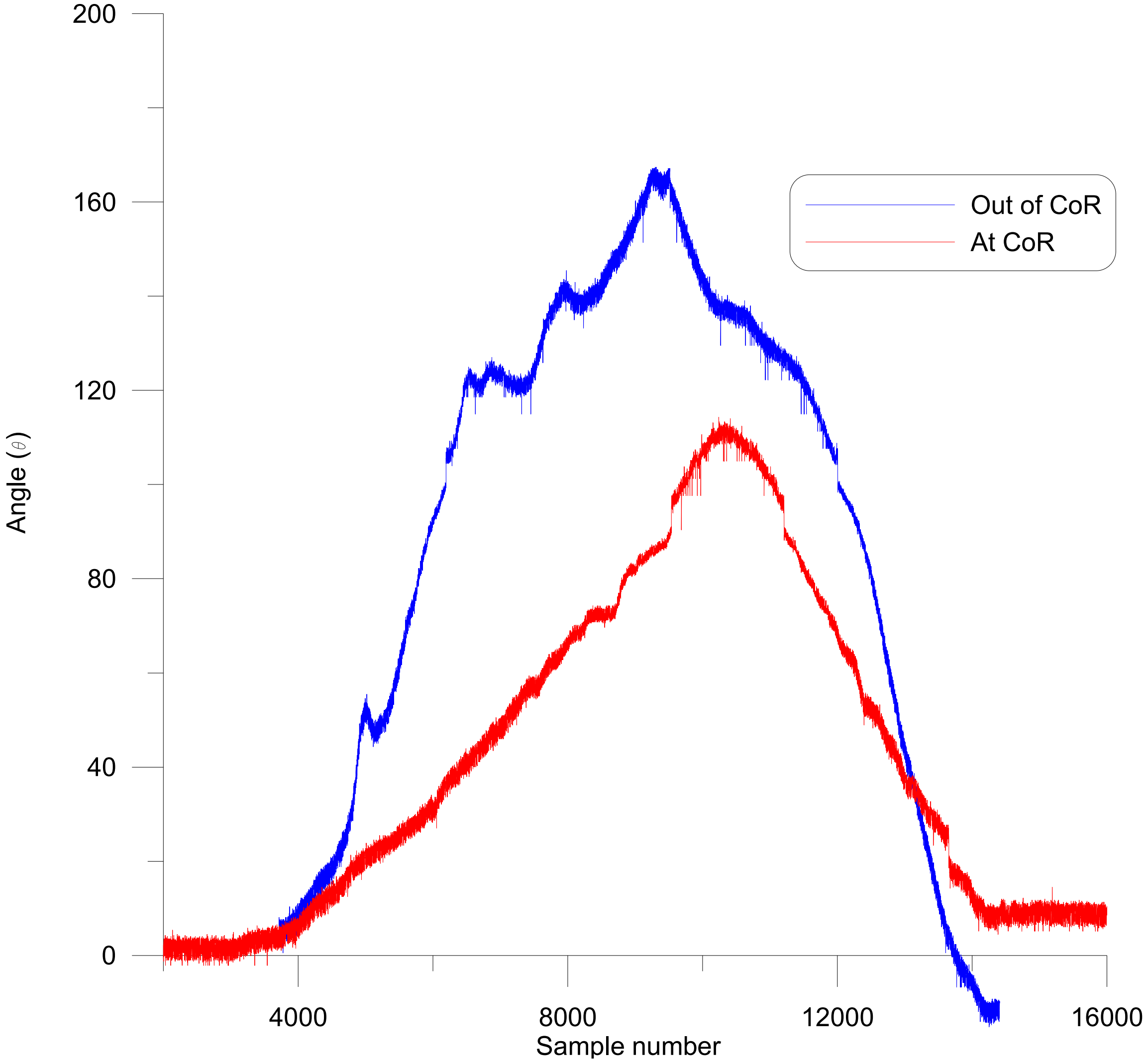

Figure 27 Two recorded signal for case A (red) and case B (blue)

The sensor records correctly the 0–120-0 degrees manoeuvre in case A but not in case B. The angle measured in case B is larger in magnitude of angle-time curve has a larger slope (higher angular speed) than those recoded in case A both as the angle increases and decreases. This proves our hypothesis that the deviations seen during the feasibility study were due to the placement of the sensing element and magnetic source outside the center of the joint rotation. In order for the portable version of the sensor to measure quantitatively precise joint angles, as it did in the tabletop version, the sensing element and magnetic source must be placed at the center of joint rotation. On the other hand, the experiment verifies that the sensor measurements are qualitatively valid as far as distinguishing the direction of rotation and large and small angles of rotation.

These results also explain the saturation of the angle measured by the joint sensor for large upper arm flexion angles as shown in figures 22–25. As the upper arm moves with respect to the torso, the flux lines seen by the sensing element change their orientation due to the change in the upper arm flexion angle and the exposure of the sensing element to a different area of the magnetic field. Saturation of the measured angle by the joint sensor appear to indicate that these two effects are countering each other to produce a constant angle reading while the upper arm flexes and extends at a high flexion angle. This indicates that the saturation angle will vary depending on the configuration of the sensing element and the magnetic source.

The sensor also requires that the intensity of the magnetic field should be at least 500 gauss. To verify that variation in the magnetic field intensity did not affect the measured angle, another experiment was conducted. While maintaining the sensing element and magnetic source at the center of rotation, using a magnetometer the vertical distance between the magnetic source and the sensing element was varied as follows:

1. Close to the sensor: field intensity = 3900 gauss
2. Further from the sensor: field intensity = 1800 gauss
3. Away from the sensor: field intensity = 100 gauss.

The field intensity was measured using the

The magnet was attached to the shaft of a DC stepper motor to assure that the same motion pattern was re-produced in the three test cases. The staircase angular position curves recorded in trials (1) and (2) were identical as shown in figure 28, however the sensor produced zero output in trial (3) indicating that field intensity does not affect the measured angle and that the sensor measures the change in the magnetic flux-lines direction only when the minimum intensity requirement is met.

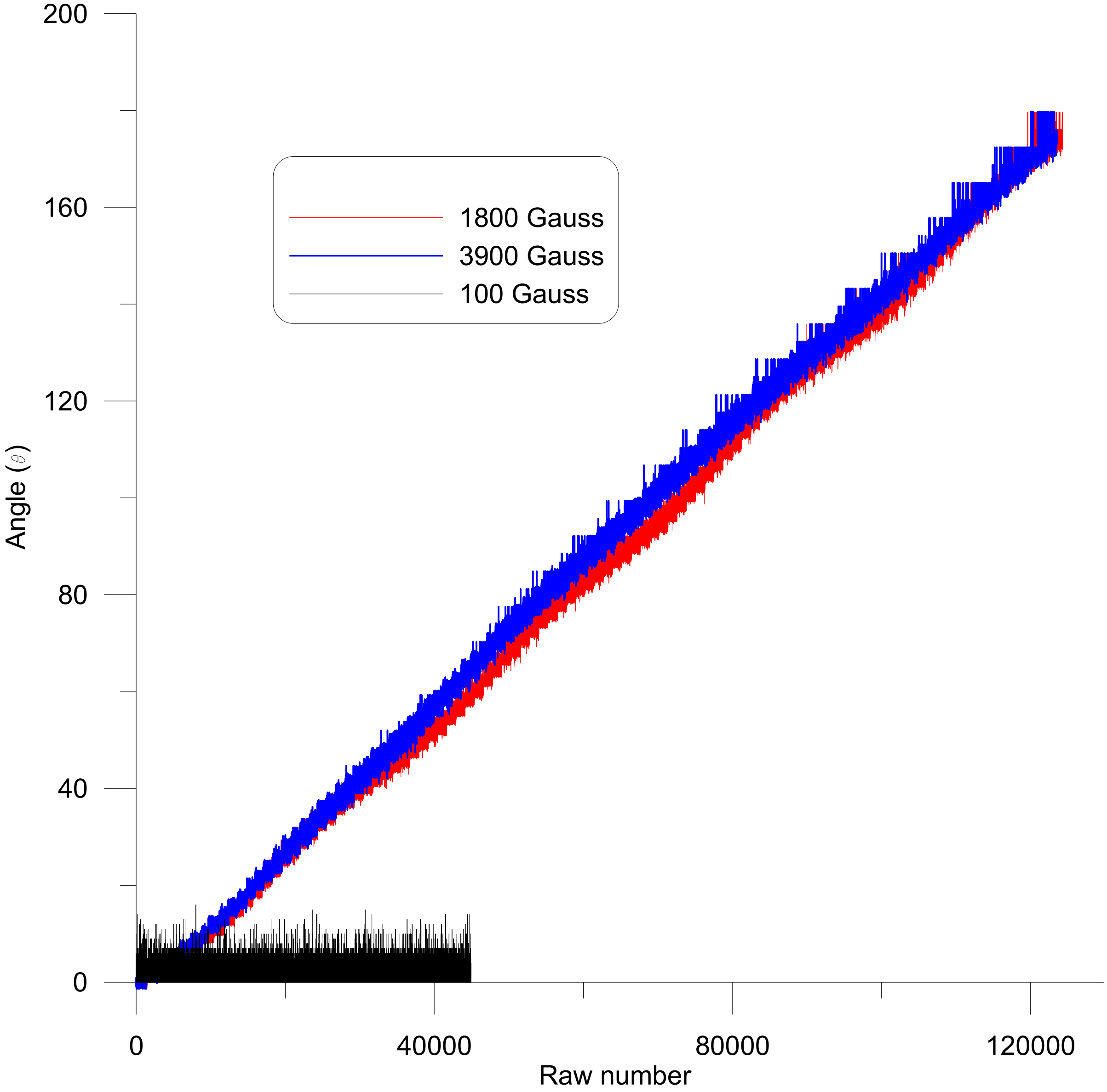

Figure 28 The effect of field intensity on sensor reading

5.2 Discrete state sensor

The discussion above reveals that the external musculoskeletal joint angle sensor in its current configuration cannot provide a quantitative measure of the angle of upper arm elevation with respect to the torso. To provide a quantitatively valid measurement of the upper arm-torso angle, the KMA200 sensing element and the magnetic source must be placed at the center of the shoulder joint in order to obtain a reliable quantitative measure of the upper arm flexion angle. This condition cannot be satisfied *in-vivo*. However, the discussion also shows that the joint sensor can provide qualitative measures of the direction of angular motion, flexion or extension, and the relative size of angular displacement.

Therefore, the joint sensor can be used as a classifier to classify the upper arm angular position into either a safe bin or a dangerous bin. Specifically, if the joint sensor proves that it can repeatedly determine whether the upper arm is above or below the threshold of the safe work envelope then it can be used as a reliable classifier of worker posture.

Different joint sensor configurations were devised and tested to determine the feasibility of this approach. The different setups were tested against two criteria:

a) reliability as a classifier of worker posture into safe and dangerous states and

b) elimination of saturation of the measured angle.

It was found that a configuration that satisfies these criteria can be achieved as follows and the results are shown in figures 29-31:

- The sensing element is placed on the axilla directly anterior to the scapula and distal to the acromion at 0.13 of the torso length.
- The magnet source is to be mounted on the medial side of the upper arm and distal to the shoulder joint at 0.2 of the upper arm length.

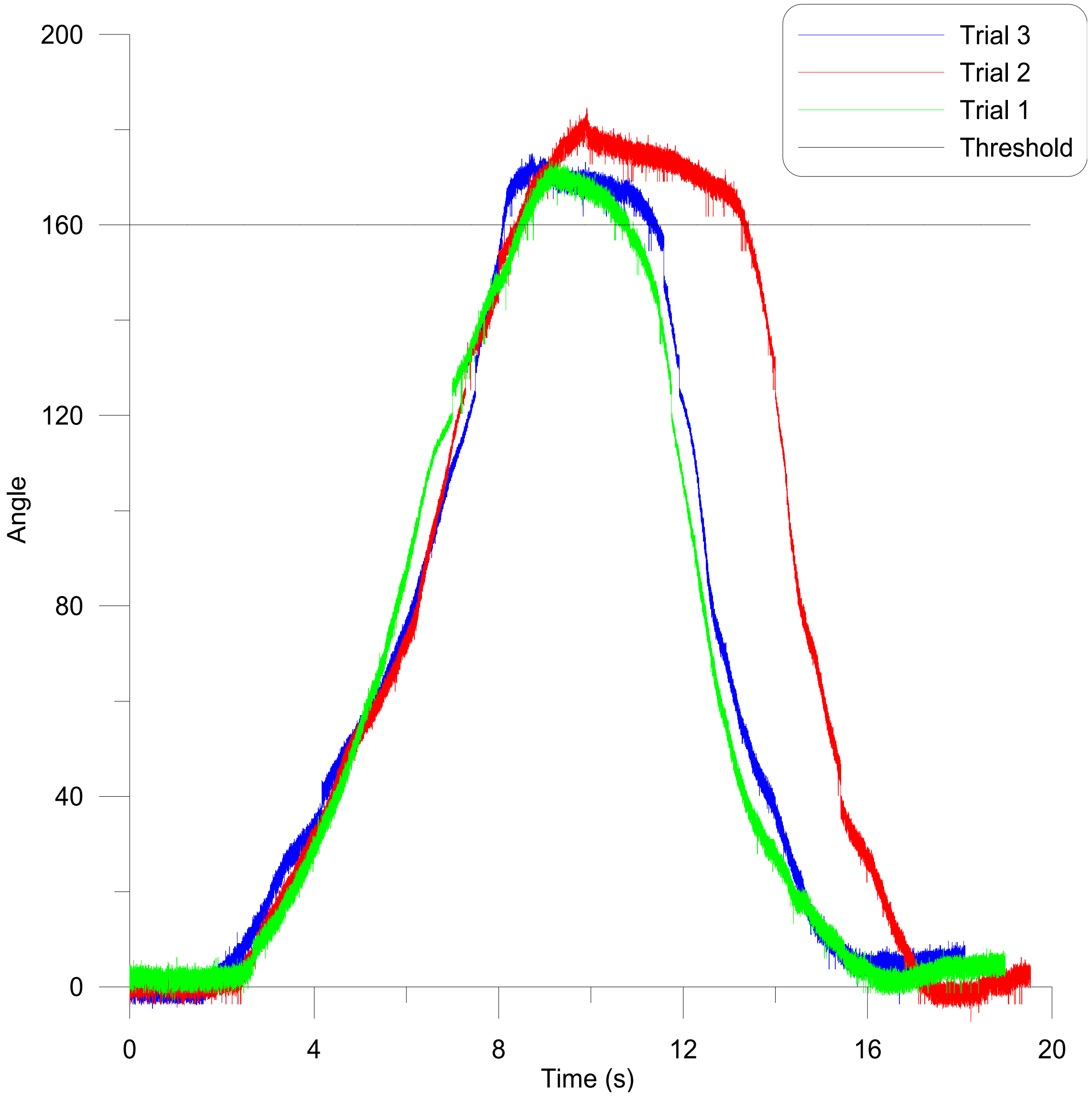

Figure 29 Sensor repeatability test on the proposed configuration

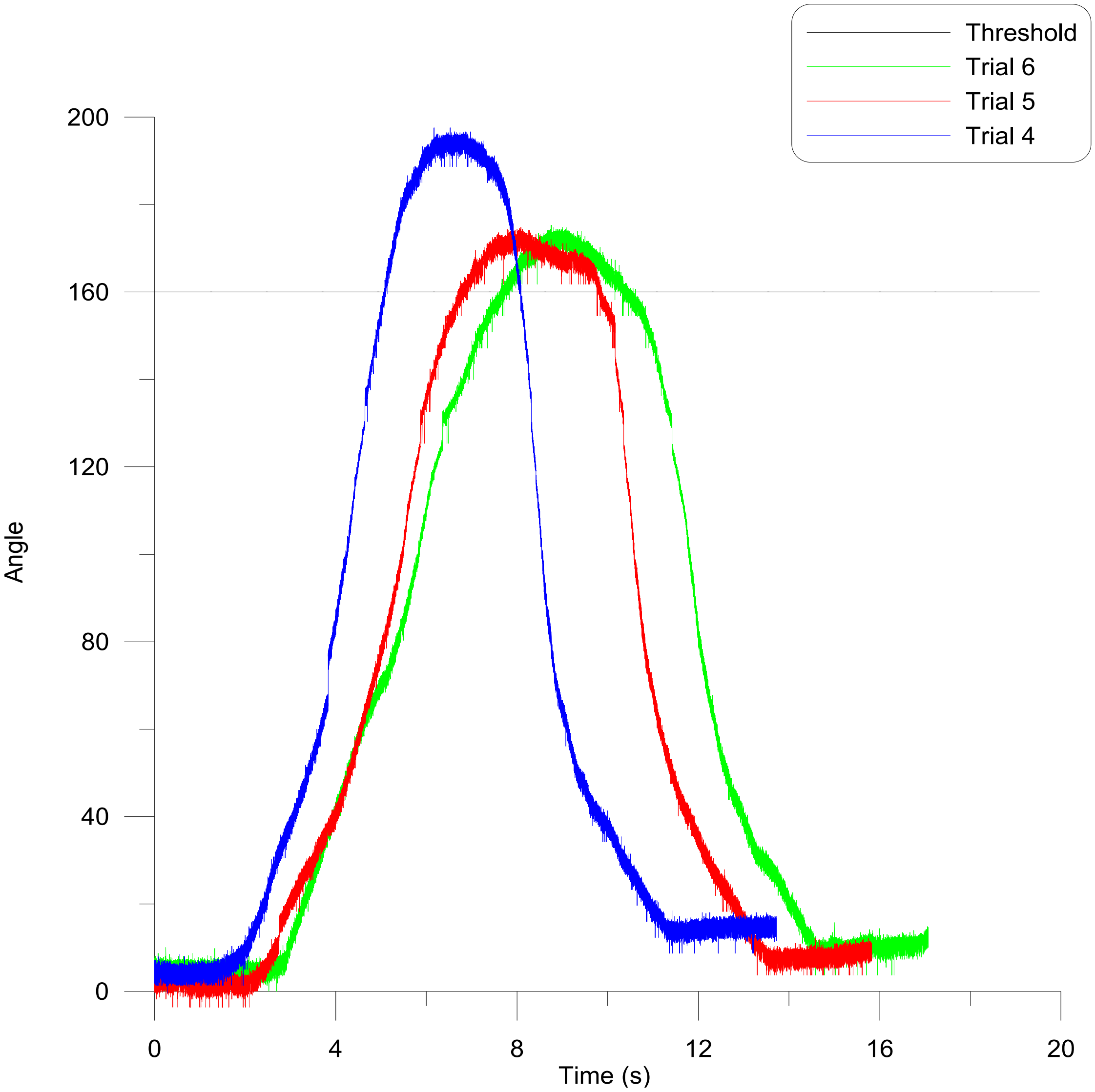

Figure 30 Sensor repeatability test on the proposed configuration

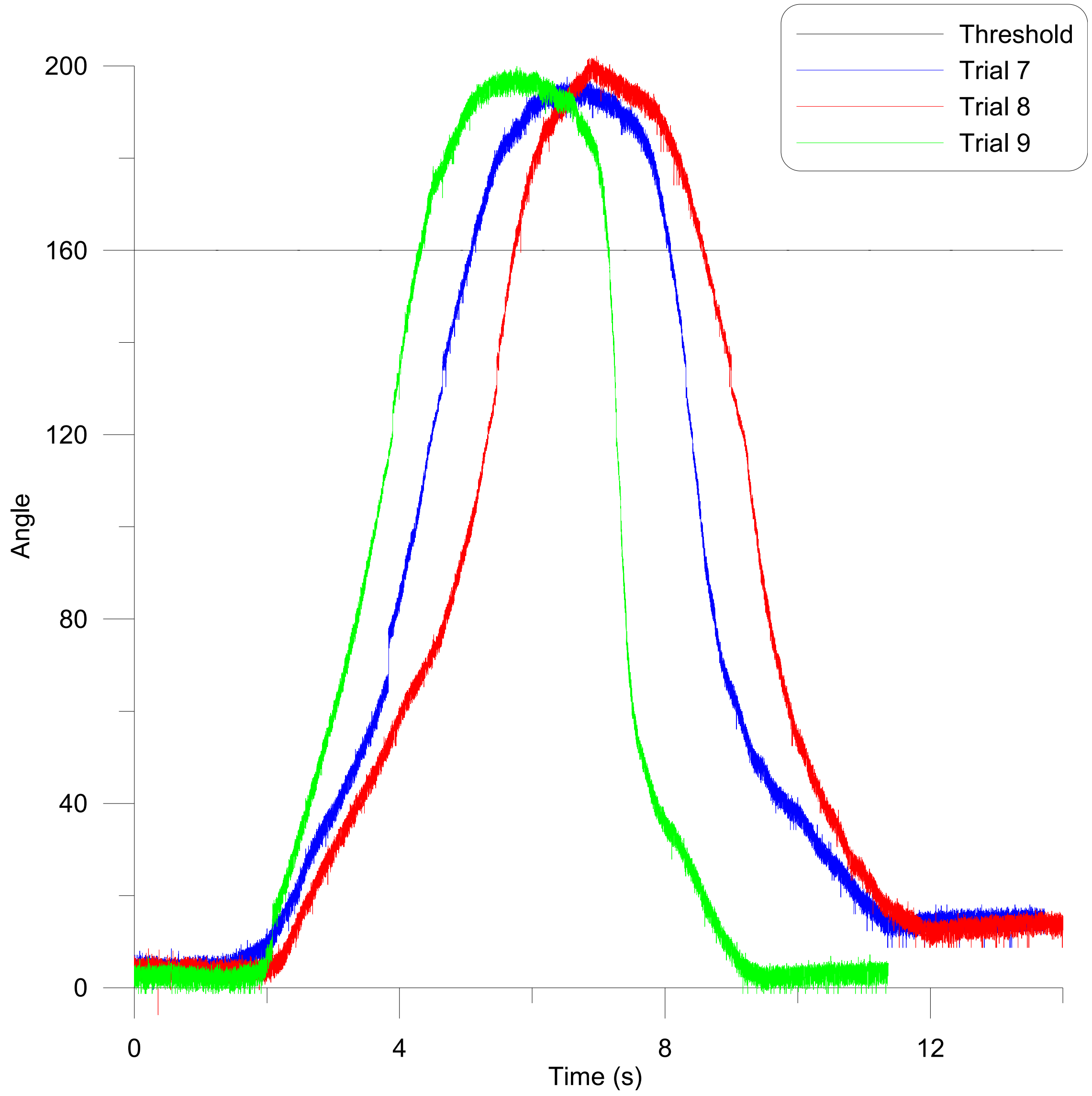

Figure 31 Sensor repeatability on the proposed configuration

The joint angle recorded using the joint sensor during 9 trials and this configuration are shown in the figures 29 – 31. All trials were conducted by one subject who performed a continuous flexion of the upper arm to a position above 90^{o} flexion followed by extension back to initial position. The threshold at 160^{o} shown in the figures was found by recording the angle reading of the joint sensor while the upper arm was held stationary at 90^{o} flexion during an independent trial.

The results show that the joint sensor can distinguish flexion and extension motions and differentiate between large and small flexion angles mimicking the qualitatively valid results of the previous experiment. Further, the threshold of the safe/dangerous motion envelopes at 90^{o} flexion was repeatedly shown to lie within the measurable flexion range under this configuration of the sensor. This was true even though the trials varied in duration and maximum flexion angle and thereby in the angular speed of flexion, which shows reasonable sensor tolerance to variability. Therefore, the sensor can be used as a classifier of shoulder posture for the purposes of decreasing the prevalence of shoulder injury among construction workers. Furthermore, the elimination of saturation means that a one-to-one map can be established between the actual upper arm flexion angle and the angle recorded by the joint sensor. This will allow the joint sensor to be used in conjunction with a lookup-table as an angular position sensor in biomechanical applications.

The use of the external musculoskeletal joint angle sensor, in its current form, for quantitative measurement of the upper arm angular position is cumbersome since calibration of the sensor, creation of a lookup-table, will be required for each sensing system configuration. Further, any displacement of the sensing element or the magnetic source from its pre-set position will invalidate the current lookup-table.

Therefore, the current sensor configuration is able to classify the movement meaning it can identify whether the worker is above or below the certain angle but not quantitatively measure it.

5.3 Conclusions

Since the standard AMR sensor configuration requires that the sensing element and the magnetic source be placed along the axis of rotation, a non-invasive approach to implementing the joint sensor to human joints is to locate it along the axis of rotation outside the body.

The joint sensor in its current form is a binary sensor that can classify and count the time the shoulder joint spends in safe and dangerous postures. This meets the shoulder monitoring system requirements. However, the joint sensor is not robust in the sense that relative displacement between the sensing element and the magnetic source will void the sensor calibration and require recalibration of the sensor. This is an impractical requirement for a worksite monitoring system.

Chapter 6

Recommendations and Future Work

In this chapter, we present the conclusive findings of this work and recommend future steps to address identified shortcomings and limitations.

6.1 Recommendations

Cumulative stress shoulder injury among construction workers need a practical solution to decrease its prevalence. This thesis, presents a method to manage and reduce these injuries based on injury theory [24, 25]. It proposes to manage the long-term behavior of the worker to reduce exposure to risk factors and consequently the prevalence of shoulder injury.

A monitoring system, the external musculoskeletal joint angle sensor, was designed to implement this solution. The joint sensor was validated against a standard motion capture system. It was found that the joint sensor measurements were qualitatively valid but not quantitatively comparable to the motion capture system measurements.

6.2 Future work

We propose three methods to enhance the performance of the joint sensor:

1) Adding a fixture to eliminate relative displacement: Part of the problem with the current joint sensor is the relative translation between the magnet and the sensor, which leads the sensor to overestimate the actual angle change. We believe that the problem lies in the nature of biological joints, the center of rotation of biological joints

is always located inside the human body, which places significant limitations on non-invasive methods to measure the joint rotation. A possible solution is to locate the sensing element and magnetic source along the axis of rotation of interest outside the body. The sensor and magnet are to be held along the axis of rotation with a fixture that holds the sensor stationary while allowing magnet to rotate freely with the body. The fixture should be designed to eliminate relative displacement between the magnetic source and the sensing element while maintaining their alignment with the axis of rotation. As a result, it should be able to approach the higher accuracy performance of the tabletop version of the joint sensor demonstrated here. The fixture design should not be cumbersome to allow for the deployment of the joint sensor as a cumulative stress injury management system in construction worksites.

2) Creating a look-up table: Using the sensor configuration established in chapter 5, testing will produce angle measurement similar to those shown in figures 29-31. These figures can be compared to those obtained using a standard motion capture system to create a calibration lookup table from the 1 to 1 relationship between the two sets of angle measurements. While this method will produce quantifiable joint angle measurements, the angle range available will be limited and the sensor system will be practical only to an experimental setup.

3) Non-standard joint sensor configurations: While the previous two recommendations create a single axis joint angle sensor, we propose another class of three-dimensional joint angle sensors. In this class of sensors, multiple sensing elements can be used in conjugation with a single magnetic source to map out the magnetic field as an object, for example the upper arm, moves. Arranging the sensing element at different angles and locations of the moving segment will allow the joint sensor

system to determine the three-dimensional position of the moving segment with respect to the stationary magnetic source.

In particular, a few practical steps can be carried out to implement the first proposed joint sensor configuration.

First, extend the joint axis of rotation to a point where the sensing element and magnetic source can be placed along the axis as shown in figure 32. For example the center of shoulder joint rotation lies inside the body and the 3 movements around the joint are around 3 axes, if the each axis was extended outside the body, 3 sensing elements and 3 magnetic sources can be placed on an exoskeleton to detect the 3 rotation independently and quantitatively with less than 0.5^{o} precision which will make the device very beneficial for the fields of biomechanics, robotics, and ergonomics. Further, this idea can be applied to different joints throughout the body, if the axes of rotation were extended outside the body and each axis was instrumented with its own sensing element and magnetic source.

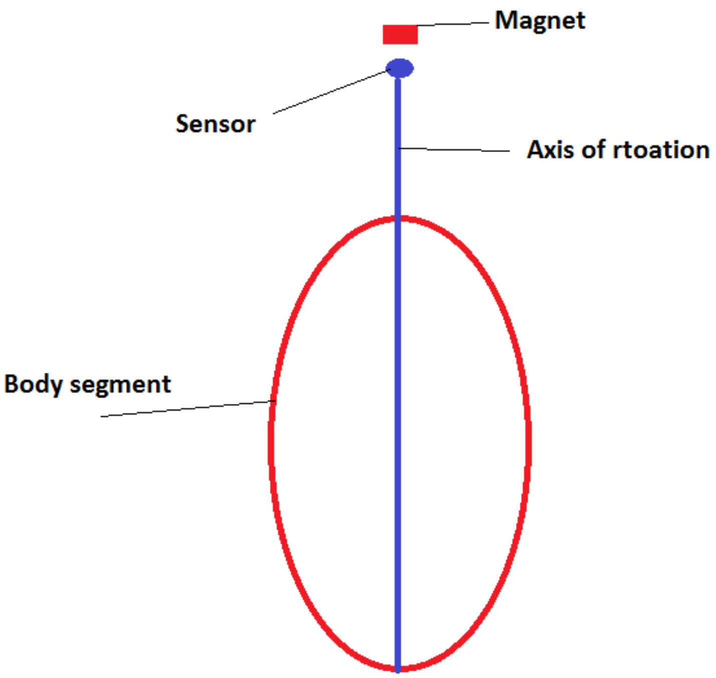

Figure 32 Extending the axis of rotation outside the body

References

[1] Bureau of Labor Statistics, "Occupational safety and health definitions," vol. 2011, .

[2] Steering Committee for the Workshop on Work-Related Musculoskeletal Injuries: The Research Base, National Research Council, *Work-Related Musculoskeletal Disorders Report and Workshop Summary. Washington DC: National Academy Press.* 1999.

[3] National Institute for Occupational Safety and Health, "Musculoskeletal disorders," vol. 2011, 2009.

[4] National Safety Council, "Management of Work-Related Musculoskeletal Disorders Accredited Standards Committee Z365 Working Draft August 2002," vol. 2011, .

[5] Bureau of Labor Statistics U.S Department of Labor, "Nonfatal occupational injuries and illnesses and requiring days away from work, 2008," vol. 2011, 2009.

[6] American Academy of Orthopedic Surgeons, "Shoulder pain," vol. 2011, .

[7] Panel on Musculoskeletal Disorders and the Workplace, Commission on Behavioral and Social Sciences and Education, National Research Council, *Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities.* 2001.

[8] Steering Committee for the Workshop on Work-Related Musculoskeletal Injuries: The Research Base, Committee on Human Factors, National Research Council, *Work-Related Musculoskeletal Disorders: A Review of the Evidence.* 1998.

[9] P. Frost and J. H. Andersen, "Shoulder impingement syndrome in relation to shoulder intensive work," *Occup. Environ. Med.,* vol. 56, pp. 494 - 498, JUL, 1999.

[10] B. P. Bernard, Ed., *Musculoskeletal Disorders and Workplace Factors. A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck,*

*Upper Extremity, and Low Back.*Cincinnati, OH.: National Institute for Occupational Safety and Health (NIOSH), 1997.

[11] C. J. English, W. M. Maclaren, C. Court-Brown, S. P. F. Hughes, R. W. Porter, W. A. Wallace, R. J. Graves, A. J. Pethick and C. A. Soutar, "Relations between upper limb soft tissue disorders and repetitive movements at work," *Am. J. Ind. Med.,* vol. 27, pp. 75 - 90, 1995.

[12] K. Ohlsson, R. Attewell, B. Paisson, B. Karlsson, I. Balogh, B. Johnsson, A. Ahlm and S. Skerfving, "Repetitive industrial work and neck and upper limb disorders in females," *Am. J. Ind. Med.,* vol. 27, pp. 731 - 747, 1995.

[13] H. Sakakibara, M. Miyao, T. Kondo and S. Yamada, "Overhead work and shoulder-neck pain in orchard farmers harvesting pears and apples," *Ergon.,* vol. 38, pp. 700 - 706, 1995.

[14] K. Ohlsson, G. Hansson, I. Balogh, U. Strömberg, B. Pålsson, C. Nordander, L. Rylander and S. Skerfving, "Disorders of the neck and upper limbs in women in the fish processing industry," *Occup. Environ. Med.,* vol. 51, pp. 826 - 832, 1994.

[15] J. Andersen and O. Gaardboe, "Musculoskeletal disorders of the neck and upper limb among sewing machine operators: a clinical investigation," *Am. J. Ind. Med.,* vol. 24, pp. 689 - 700, 1993.

[16] H. Chiang, Y. Ko, S. Chen, H. Yu, T. Wu and P. Chang, "Prevalence of shoulder and upper limb disorders among workers in the fish processing industry," *Scand. J. Work Environ. Health.,*vol. 19, pp. 126 - 131, 1993.

[17] K. Ohlsson, R. Attewell and S. Skerfving, "Self-reported symptoms in the neck and upper limbs of female assembly workers," *Scand. J. Work Environ. Health.,*vol. 15, pp. 75 - 80, 1989.

[18] B. Stenlund, I. Goldie, M. Hagberg, C. Hogstedt and O. Marions, "Radiographic osteoarthrosis in the acromioclavicular joint resulting from manual work or exposure to vibration," *Br. J. Ind. Med.,* vol. 49, pp. 588 - 593, 1992.

[19] A. Bjelle, M. Hagberg and G. Michaelsson, "Clinical and ergonomic factors in prolonged shoulder pain among industrial workers," *Scand. J. Work Environ. Health,* vol. 5, pp. 205 - 210, 1979.

[20] P. Herberts, R. Kadefors, C. Högfors and G. Sigholm, "Shoulder pain and heavy manual labor," *Clin. Orthop.,*vol. 191, pp. 166–178, 1984.

[21] C. L. Levitz and J. P. Iannotti, "Overuse injuries of the shoulder " in *Repetitive Motions Disorders of the Upper Extremity*, S. L. Gordon, S. J. Blair and L. J. Fine, Eds. Rosemont, IL: American Academy of Orthopedic Surgeon, 1995, .

[22] J. Kim, M. K. Chung and J. S. Park, "Measurement of physical work capacity during arm and shoulder lifting at various shoulder flexion and ad/abduction angles," *Int. J. Ind. Ergonomics,* vol. 13, pp. 153-163, 2003.

[23] S. W. Svendsen, J. P. Bonde, S. E. Mathiassen, K. Stengaard-Pedersen and L. H. Frich, "Work related shoulder disorders: quantitative exposure-response relations with reference to arm posture," *Occup. Environ. Med.,* vol. 61, pp. 844 - 853, OCT, 2004.

[24] S. Mcgill, "The biomechanics of low back injury: implications on current practice in industry and the clinic," J.Biomech.,vol. 30, pp. 465-475, 1997.

[25] S. Kumar, "Theories of musculoskeletal injury causation," Ergon.,vol. 44, pp. 17-47, 2001.

[26] R. Takeda, S. Tadano, M. Todoh, M. Morikawa, M. Nakayasu and S. Yoshinari, "Gait analysis using gravitational acceleration measured by wearable sensors," *J. Biomech.,* vol. 42, pp. 223 - 233, 2009.

[27] K. Tong and M. H. Granat, "A practical gait analysis system using gyroscopes," *Med. Eng. Phys.,* vol. 21, pp. 87 - 94, 3, 1999.

[28] H. Zhou, T. Stone, H. Hu and N. Harris, "Use of multiple wearable inertial sensors in upper limb motion tracking," *Med. Eng. Phys.,* vol. 30, pp. 123 - 133, 2008.

[29] J. Naito, G. Obinata, A. Nakayama and K. Hase, "Development of a wearable robot for assisting carpentry workers," *Int. J. Adv. Robotic. Sy.,* vol. 4, pp. 431 - 436, 2007.

[30] B. R. Picco, S. L. Fischer and C. R. Dickerson, "Quantifying scapula orientation and its influence on maximal hand force capability and shoulder muscle activity," *Clin. Biomech.,* vol. 25, pp. 29 - 36, 2010.

[31] W. M . Keyserling, M. Brouwer, B. A. Silverstein, "A checklist for evaluating ergonomic risk factors resulting from awkward postures of the legs, trunk and neck," Inter. *J. Ind. Ergon*., vol. 9, p.283 , 1992 .

[32] G. Ogris, T. Stiefmeier, H. Junker, P. Lukowicz and G. Troster, "Using ultrasonic hand tracking to augment motion analysis based recognition of manipulative gestures," in *Ninth IEEE International Symposium on Wearable Computers (ISWC'05), 2005,* 2005, pp. 152-159.

[33] R. Zhu, Z. Zhou, "A real-time articulated human motion tracking using tri-axis inertial/magnetic sensors package" *IEEE Trans Biomed Eng*, vol.12 , p.295 , 2004

[34] T. Ehlgen,T. Pajdla, "Monitoring surrounding areas of truck-trailer combinations," in *Proceedings of the 5th International Conference on Computer Vision Systems* (2007).

[35] G. Rieger, K. Ludwig, J. Hauch, W. Celmens, "GMR sensor for contactless position detection," *Sens. and Actuat. A.,* vol. 91 pp. 7-11. 2001

[36] C.P.O. Treutler, "Magnetic sensors for automotive applications," *Sens. and Actuat. A.,* vol. 91 pp. 2-6. 2001

[37] A. Felscher, "Application note programmable angle sensor KMA200," 2004.

Appendix A

External Musculoskeletal Joint Angle Sensor Test protocol

Using Vicon 3D cameras + External musculoskeletal joint sensor, a set of markers will be placed on a participant to track the upper arm to torso angle of elevation in 2D (sagittal plane) in addition to wearing External Musculoskeletal Joint sensor to perform the following movements in the sagittal plane (2D).

Movement	Participant number	File name
0 – 180^0 upper arm extension		
0 – 180^0 upper arm extension		
0 – 180^0 upper arm extension		
0 – 180^0 upper arm extension		
0 – 180^0 upper arm extension		

- The participant will be wearing a set of 19 markers listed in table 2.
- The participant will perform each movement with a pause at the beginning and the end of each movement to synchronize the sensor system with motion capture technique.
- The participant will perform 5 repeats.

Appendix B

Table 2 Pinning information for portable version (PIC18F87J50)

Pin number	Symbol	Description
11	VSS	Ground
12	VDD	Voltage supply
16	D+	Positive data to USB
17	D-	Negative data to USB
20	OSC	Circuit oscillation
32	VDD	Voltage supply
33	VSS	Ground
34	PMD5	Write protect pin
44	SCK1	Synchronize clock
45	SDI1	Data input from MCU
46	SDO1	Data output to MCU
48	VDD	Voltage supply
49	CLKI	Input Timing for MCU
50	CLKO	Output Timing for MCU
51	VSS	Ground
54	RB4	Signal detector from SD
55	RB3	Chip select SD
58	RB0	Acquire data from MCU

Pin number	Symbol	Description
70	VDD	Voltage supply
71	VSS	Ground