University of Strathclyde

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Movement Strategy Identification in Activities of Daily Living: A Clinical Investigation of Knee Bearings

By

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Στην Ολυμπίτσα.

ὁ δέ ἀνεξέταστος βίος οὐ βιωτὸς ἀνθρώπῳ

an unexamined life is not worth living

-Socrates (the other one)

Signed:

Date:

PREVIOUSLY PUBLISHED WORK

PUBLICATIONS

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ABSTRACT

Introduction: Osteoarthritis is one of the leading causes of disability, and the knee joint is the most commonly affected site in the body. The last resort for treatment of end-stage knee osteoarthritis is total knee arthroplasty surgery. Despite the plethora of implant designs, the current evidence on which bearings give the most natural movement and function is still scarce. **Aims:** the aim of this study was to compare the functional performance of fixed and mobile bearings, with different degrees of congruency. **Methods:** participants underwent 3D motion capture analysis during two activities of daily living. Patient participants were recorded before, four to six weeks after, and a year after the operation. Pain and satisfaction levels were also surveyed using bespoke questionnaires and the Oxford knee score. Participants' functional performance was accessed by means of an innovative statistical procedure (i.e. hierarchical clustering), that fruitfully classified movement patterns, and discerned healthy from unhealthy movement behaviours. **Results:** osteoarthritic participants used different movement strategies compared to healthy individuals. Patient participants' arm and feet behaviour was often categorised as asymmetrical, indicating the presence of compensation mechanisms due to weakness of the affected join. Post-operational behaviour tends to converge to the controls' performance. No differences were observed due to knee implant allocation, or anthropometric characteristics. Questionnaire analysis revealed significant improvement post-operatively in the self-assessment of patient participants, but with no eminent correlation between implant design and outcome measures. **Conclusion:** the proposed hierarchical clustering procedure managed to adequately, rapidly and reliably evaluate changes in the movement habits of patients after total knee arthroplasty, and access their improvement throughout their rehabilitation process.

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ACL	Anterior Cruciate Ligament
ADL	Activities Of Daily Living
ANOVA	Analysis of Variance
ASIS	Anterior Superior Iliac Spine
BMI	Body Mass Index
COM	Centre Of Mass
DOF	Degrees Of Freedom
FPS	Frames Per Second
GRF	Ground Reaction Force
HC	Hierarchical Clustering
OA	Osteoarthritis
OKS	Oxford Knee Score
PIG	Plug-In-Gait Model
PCL	Posterior Cruciate Ligament
ROM	Range Of Motion
STS	Sit-To-Stand
STW	Sit-To-Walk
TKA	Total Knee Arthroplasty
TKR	Total Knee Replacement
3D	Three Dimensions

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Arthritis (plural: arthritides) originates from the Greek 'arthron' (ἄρθρον) for joint and the Latin 'itis' for inflammation, and refers to a disorder of one or more joints. Osteoarthritis (OA) is the most common form of arthritis, affecting about 8.75 million people in the UK alone; this is equivalent to 33% of the population over 45 years of age. While OA can manifest in any joint of the body, the knee is the most common site (accounting for 59% of all cases in the United Kingdom), followed by the hip (33%), and ankle (7%). The number of patients with knee OA is estimated to reach 6.5 million by 2020 (Mobasheri and Batt, 2016).

Total knee arthroplasty (TKA) surgery is carried out as a last resort treatment, relieving pain and disability in end stage OA, with high long-term survival rates: in a 12-years study of 164 OA patients after TKA, there were two cases of infection, and one case of mechanical loosening with an overall 97% success rate (Stein and Taylor, 2004). Due to the increasing life expectancy, and TKA being offered to younger patients, the number of procedures will increase. Younger and more active patients produce a demand for durable knee implants with improved functional performance.

The natural knee joint movement involves flexion, extension, rotation and sliding. At the beginning of flexion, the femur slightly rotates laterally which eases collateral ligament’s tension, allowing flexion to follow. Throughout flexion, the menisci are dragged posteriorly. At maximum flexion, the posterior cruciate ligament (PCL) elongates, preventing the femur from sliding forward on the tibia. As the knee extends, the condyles of the femur roll on the tibial condyles, while the anterior cruciate ligament (ACL) prevents the knee from over-extension. Near full extension, the femur is rotated medially, the collateral ligaments are contracted, and the knee is locked.

This is a challenging movement to replicate in a knee implant design. Today’s mechanical knee implants have a femoral component which replaces the distal end of the femur, and a tibial component which substitutes the proximal tibia. In exchange of the menisci, a polyethylene insert is added between the femoral and tibial components to provide a bearing surface.

A plethora of both major and minor design choices exists, providing different approximations to the movement of the natural knee. These design variations include distinct types of bearing surface (fixed and mobile bearing designs), degrees of congruency (fully and partially congruent), methods of fixation (cemented or uncemented), posterior cruciate ligament management (salvage or sacrifice), and type of constraint (cone-in-cone or tibial tray designs).

The success of TKA is quantified by clinical patient reported outcome questionnaires. The Western Ontario and McMaster University Osteoarthritis Index (WOMAC), and the Oxford Knee Score (OKS) are most frequently used (Kia et al., 2014). However, these clinical knee scoring systems make it difficult, or even impossible, to detect subtle differences between patients' performance (Komnik et al., 2015). What is more, the OKS in insensitive to post-operative differences, and thus, it may not be ideal for studies comparing functional outcomes after TKA. To overcome such difficulties, multidimensional gait analysis methods have been used to report functional post-operative differences (Lim et al., 2015, Urwin et al., 2014, Li et al., 2013, Coffey et al., 2011, Farquhar et al., 2009, Adams and Cerney, 2007, Smith et al., 2006, Catani et al., 2003). Yet, despite the excess of assessment tools and methods to compare implant bearings, the up-to-date evidences on which design better simulates the native knee are unclear.

1.2 AIMS OF THE STUDY

This thesis reports a subgroup analysis of the study "Biomechanical Assessment of a High Congruency Knee Bearing" registered at www.clinical trials.gov as NCT02422251.

Recruited patients were randomised to receive one of three different variants of the Columbus® (Aesculap AG, Germany) knee prostheses. Two of these, are high-congruent posterior stabilised bearings, while the last one has a low-congruent cruciate retaining design. Posterior stabilised bearings require the posterior cruciate ligament (PCL) to be resected. One of the high congruent knee implants, has a rotating platform, while the other two are fixed bearings. All the implants in this study were fixed with cement on both the femoral and tibia side. No patient was recruited in this study if the randomisation would leave him/her clinically or functionally disadvantaged.

This is a double blind randomised controlled trial. The purpose of the study is to compare the biomechanical performance of three knee replacements with different bearing designs to that of a native or natural knee. The hypothesis is that a mobile bearing design with a high congruency bearing will allow the knee replacement to work more like the native knee and give more natural movement when carrying out everyday tasks.

The current evidence on whether fixed or mobile, low or high congruent bearings give the most natural movement or provide better knee function is ambiguous (Poirier et al., 2015, Tjørnild et al., 2015, Capella et al., 2016, Huang et al., 2007). By carrying out a randomised controlled trial, including a cohort of healthy individuals, and taking in-depth functional assessments of several different common activities of daily living, it should be possible to show what level of functional outcome the three bearings being used give.

The study aims to:

1. To determine which bearing provides closer to normal post-operative function during activities of daily living.
2. To determine the improvement in function post-operatively compared to pre-operative.
3. To identify functional differences between the three patient groups compared to the control group.

The objectives of the study are:

1. To develop and establish an automated statistical procedure that can identify and classify movement patterns in activities of daily living, and

use it as a tool to assess the functional performance of people with movement impairments.

2. To compare patient reported outcome measures between groups.

1.3 THESIS STRUCTURE

CHAPTER 2 describes the anatomy and biomechanics of the knee joint, and presents the current options available for the treatment of osteoarthritis of the knee in a review of the literature. Total knee arthroplasty is described in detail, with the benefits and limitations of the most common knee implants and techniques used today. Subsequently, motion analysis and questionnaire techniques that are recurrently used for the assessment of the rehabilitation process after total knee arthroplasty are described.

The natural variability of movement patterns in human motions is an often-neglected topic, which is highlighted in **CHAPTER 3** to reinforce the motives and rationale behind a movement strategy identification technique that may be used as an assessment tool. In this chapter, the effects of starting position and task execution restrictions in the biomechanical analysis of human motion are examined. Nevertheless, the variability when measuring human motion due to the unpredictability and inconsistencies of a person's movements, is conclusively prohibitive for comparison purposes. To demonstrate this, a case study of a single participant performing the sit-to-walk task, is presented. No instructions were given regarding the initiation and execution of the task. Kinematic and kinetic variables were calculated and compared with analogous findings of control subjects from similar studies in the literature. The effects of movement strategy adoption in the biomechanical analysis are outlined, along with the necessity of an algorithm that will deal with the heterogeneity of movement behaviours and preferences.

The research objectives of the study, and the potential uses of an assessment tool for the identification of movement patterns in activities of daily living, are discussed in Error! Reference source not found.. The chapter concludes detailing h ierarchical clustering, the statistical technique that was used for the identification of movement strategies.

CHAPTER 5 outlines the protocol design and the ethical limitations of the study. Patient groups are defined, along with the type of raw clinical data that were routinely collected. Processing of motion analysis and questionnaire data for the two recorded activities of daily living, the sit-to-walk and the car ingress tasks, is also detailed.

Further processing of the motion capture data, specifically for the purpose of identifying motion strategies, movement asymmetries, and the division between healthy and unhealthy movement patterns, is described in **CHAPTER 6: Results.** In addition to the hierarchical clustering of the recording trials, the chapter concludes with the statistical analysis of the Oxford knee scores and bespoke questionnaires.

Discussion and conclusions over the analysis of the sit-to-walk and car ingress tasks are presented in penultimate section of this thesis, **CHAPTER 7: Discussion and** Conclusion**.** This includes a discussion over the implications of the findings, and a comparison of the results with the limited existed bibliography. In addition to the results obtained by means of hierarchical clustering, the chapter discusses over the inadequacy of the Oxford knee score questionnaire, to detect subtle differences in the progress of total knee arthroplasty patients throughout their rehabilitation.

The entire research project is summarised, and the implications of the findings are discussed, in the concluding part of the thesis, **CHAPTER 8: Summary.** The closing section of this work proposes suggestions for future works.

CHAPTER 2. LITERATURE REVIEW

2.1 THE KNEE JOINT

2.1.1 Bony structures

The knee joint is the largest synovial joint of the human body and is formed between three bones, the femur, patella and tibia. Although it is often considered as a hinge joint, the motion of the knee is far more complicated due to the rotation freedom that it provides. The joint itself consists of two different interfaces, the tibiofemoral and the patellofemoral.

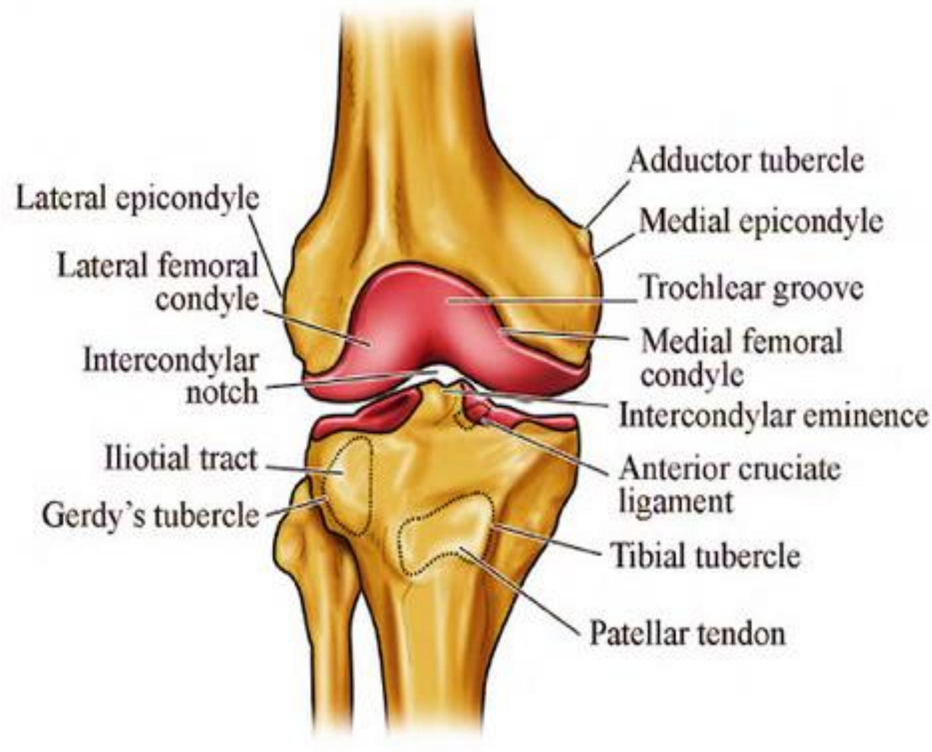

Figure 2.1 Anatomy of the knee (Scuderi and Tria, 2010).

In the tibiofemoral interface, the two curved condyles on the distal part of the femur encounter two dipped condyles at the proximal end of the tibia, in order to form the second strongest joint of the human body (**Figure 2.1**). The condyles of the femur are pear-shaped when seen from the sagittal plane; however, the medial condyle has a greater radius of curvature, and is more prominent than the lateral one. This asymmetrical anatomy, allows the bone to rotate on the tibia in all three axes of motion, while also permits a slight translation in the anteroposterior plane (Scuderi and Tria, 2010). The medial and lateral epicondyles of the femur are separated by a deep notch called intercondylar fossa (**Figure 2.1**). On the other side of the interface, the area between the two condyles on the proximal end of the tibia bone is called intercondylar eminence, and offers attachments for the medial and lateral meniscus, and the anterior cruciate ligament.

The patellofemoral interface exists between the patella and the femoral trochlear groove. The patella lies on the anterior of the knee joint. This triangular sesamoid bone is formed within the tendon of the quadriceps femoris muscle, and is linked to the tibia with the patellar ligament. The posterior face of the patella articulates with the trochlear surface of the femur. The patellofemoral joint aids in the stability of the knee, while increasing the lever arm of the extensor force by transferring the force anteriorly to the axis of rotation of the knee (Scuderi and Tria, 2010).

2.1.2 Menisci

Bones are protected by a thin coating of hyaline cartilage that provides an almost frictionless surface, while shielding the bone from wear and tear. Amid the femur and tibia exists the menisci; these cartilaginous crescent-shaped tissues cling to the horn of the tibial plateau (**Figure 2.2**). Menisci are primary composed of collagen (75%), other proteins (roughly 10%) and water (Scuderi and Tria, 2010). Menisci cover approximately 70% of the articulation area of the plateau. The periphery of the tissue is connected to the inner surface of the synovial capsule. The functions of the menisci include stress distribution across the joint, facilitation of the articulation, and prevention of soft tissue impingements (Athanasiou and Sanchez-

Adams, 2009). By increasing knee congruity, the menisci also aid in the stabilisation of the joint.

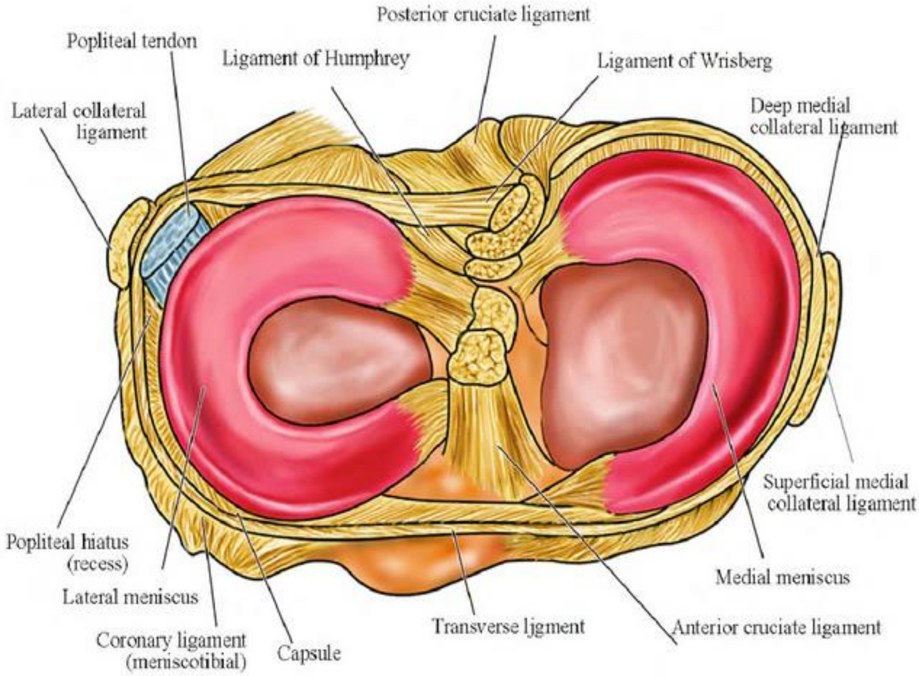

Figure 2.2 Superior view of the menisci (Scuderi and Tria, 2010).

2.1.3 Muscles

The quadricep muscle group exists in the anterior sector of the joint, and involves four muscles: the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedious. The quadriceps tendon insertion extends over the patella, and eventually converts into the patellar tendon. This tendon is located between the inferior edge of the kneecap and the tibia tubercle (Scuderi and Tria, 2010). The quadricep muscles work as the main extensors of the knee. Medially of the knee lie the sartorius and gracilis muscles, whereas the hamstrings and gastrocnemius are located at the posterior of the joint. The hamstrings are the main flexors of the joint, while the gastrocnemius helps them regulate rotation while flexing. Previous studies suggested that a significant reduction of the quadriceps muscle strength occurs with aging (Samuel et al., 2012), while quadriceps weakness can ultimately lead in the development of osteoarthritis (Segal et al., 2010).

2.1.4 Ligaments

Ligaments (**Figure 2.3**) are tough fibrous connective tissues that connect bone to bone (Darrow, 2001). The main ligaments present in the knee joint are the anterior and posterior cruciate, and the medial and lateral collateral ligaments (**Figure 2.3**) (Scuderi and Tria, 2010). The anterior cruciate ligament is the main stabilizer of the joint, and prohibits the excessive forward translation of the tibia on the femur. This ligament is approximately 32mm long and 9.5mm thick (Arliani et al., 2012). The shape of the ligament changes throughout the knee's natural movement: the anteromedial bundle fibres stiffen in full flexion, while the posterolateral ones in extension (Zens et al., 2015).

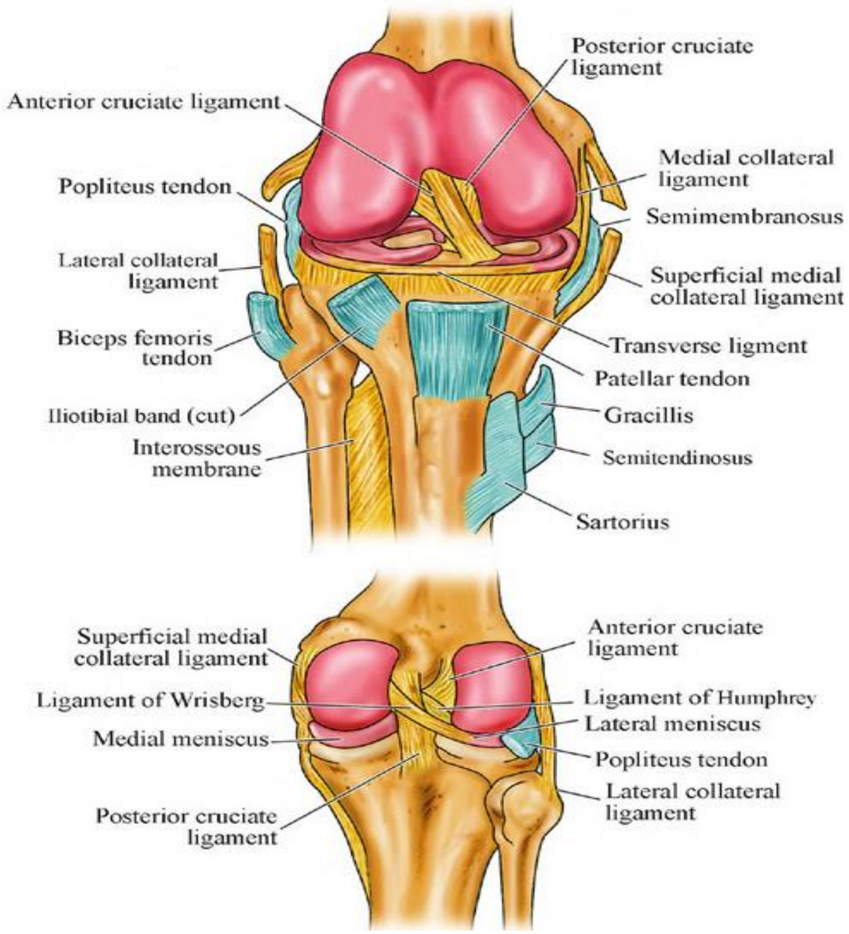

Figure 2.3 Anterior and posterior views of the knee ligaments (Scuderi and Tria, 2010).

The posterior cruciate is considered to be the most crucial knee ligament, since it is almost entirely responsible for restraining the posterior movement of the tibia on the femur. It is approximately 50% larger, and two times stronger in tensile strength (739–1,627 N) than the anterior cruciate (Amis et al., 2006). Similarly to the anterior ligament, the posterior bundle of the posterior cruciate is tight in full extension. This ligament is fixated in the intercondylar notch of the femoral condyles. It is, on average, 38mm long and 13mm wide (Harner et al., 1995).

2.2 KNEE KINEMATICS

The knee joint provides a broad range of movement and an excessive resistance to external stresses, thanks to its passive and active stabilizers. Compression and tension loads are spread among the articular surfaces, ligaments and muscle tissue. Ligaments are regarded as being passive/elastic components, and can only be loaded by tensile forces. Muscle and tendons behave similarly but they are considered as active structures. Bones are non-elastic, and work under compressive stresses (Affatato, 2015).

Proper knee kinematic behaviour is essential for the joint function. Changes in the loading of the joint, and overloading of the articulation surfaces may lead to degenerative conditions. In the tibiofemoral interface, the distal end of the femur and the proximal end of the tibial bone articulate creating a system with six degrees of freedom (**Figure 2.4**). The three translations are excessively limited by the fibrous capsule, the ligaments and the muscles of the knee. Apart from the flexion and extension of the joint, both the abduction/adduction and internal/external rotation movements are restricted as well.

The normal flexion and extension range of the knee, drifts from 0˚ to 140˚ (Roach and Miles, 1991). This range deviates based on the undertaken type of activity: during walking, approximately, up to 70˚; climbing up to 90˚; running up to 110˚ (Novacheck, 1998). Knee flexion is a result of a mixture of both rolling and sliding of the femur on the tibial plateau. This complex movement, also known as rollback, permits the extensive rotation of the joint on the anteroposterior plane: without the sliding of the femur on the tibia plateau, the joint would dislocate since the articular surface on the proximal tibia head would be too small; without the rolling, the flexion would be limited due to possible tissue impingement. Thus, the combination of those two movements allows an excessive degree of bending without compromising the joint's stability and function (Affatato, 2015).

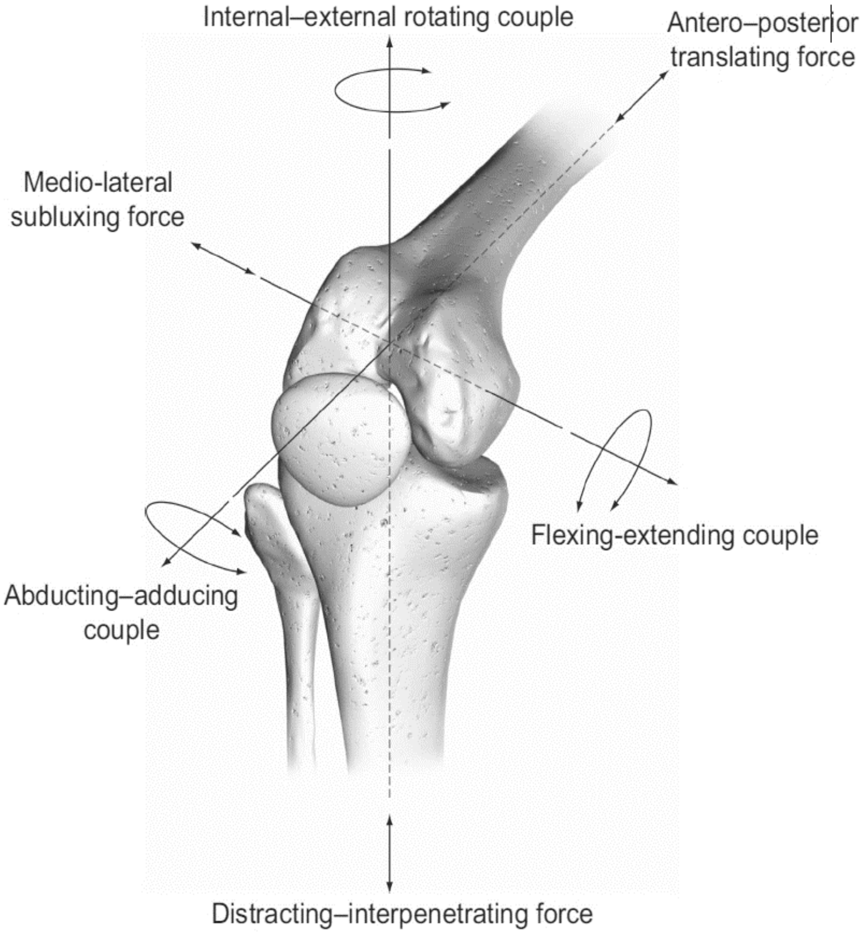

Figure 2.4 The rotations and translations of the knee (Affatato, 2015).

Even though the knee may be considered as a hinge joint, the centre of rotation is not static throughout the range of motion. The continuous centre of rotation lies above the contact area of the joint, and travels on a crescent path (**Figure 2.5**) (Smidt, 1973). It is also suggested that the cruciate linkage is responsible for the kinematic conditions that lead to the translation of the centre of rotation of the knee

(Burgess et al., 1997). The variation in the location of the centre of rotation, significantly complicates the design of a prosthetic knee that can operate in a natural manner.

Medial rotation causes the foot to rotate internally towards the centre of the body; lateral rotation moves it externally. Mediolateral rotations take place in the horizontal plane and they are correlated to the extent of flexion of the joint. This movement is referred as "screw-home" (Hallen and Lindahl, 1966) and is responsible for a minor degree of medial rotation during full flexion, and a minor lateral rotation during full extension. Knee extension and flexion are also linked to a passive abduction/adduction movement. Nevertheless, motion in the frontal plane is only limited to a few degrees due to the surrounding soft tissues.

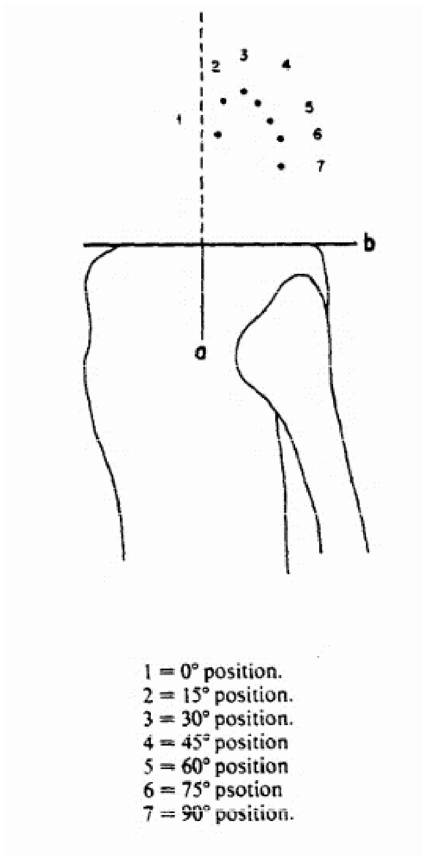

Figure 2.5 Pathway of continuous centre of rotation with respect to the tibia and femur (Smidt, 1973).

2.3 KNEE KINETICS

Dynamic analysis determines the forces and moments acting on the knee joint (**Figure 2.6**). The forces acting on the tibiofemoral joint fluctuate between 2.8 to 3.4 times the total body weight when walking, while at the same time, the patellofemoral joint may receive forces from 0.8 to 2.6 times the body weight (Smidt, 1973). When walking on an incline, the compressive forces on the tibiofemoral interface may reach up to 5 times the body weight, while walking downhill can dramatically increase the load eightfold (Doral et al., 2011).

As mentioned previously, the tibiofemoral contact area decreases significantly while the knee flexes due to the femoral rollback. Consequently, load is transmitted over a smaller area, resulting in the distribution of higher stresses during knee flexion. This magnification effect due to the small contact area of the tibia and femur, is the reason why tasks such as stair climbing, and incline walking are considered to be high impact activities. Due to these disproportionate forces acting on the joint, the knee is more exposed to wear and tear.

A percentage of this load is naturally absorbed by the tissues and muscles of the lower limbs. Nevertheless, aging was shown to affect muscle mass and muscle strength after the age of 30 (Keller and Engelhardt, 2013). Muscle atrophy shifts the weight bearing demands to the bones' interface; this, along with cartilage deterioration, can lead to bones rubbing against each other, and therefore increasing bone damage in the elderly population.

2.4 OSTEOARTHRITIS OF THE KNEE

The prevalence of OA is chiefly correlated with age, sex and obesity. Symptomatic knee OA occurs in 10% of men and 13% of women over 60 years of age (Zangi et al., 2015). Obesity account for 21% of the risk of developing OA of the knee, while family history, previous trauma, and previous meniscectomy collectively account for 18% (Heidari, 2011). Heritability factor and mutations in the genes for type II collagen have also been correlated with the development of OA. Even though there is undoubtedly a genetic predisposition, particularly in hand and knee OA in women, the genetics of the disease are not yet fully understood (Heidari, 2011). Osteoarthritis is rarely seen in people under the age of 45; in such cases, the condition is due to trauma or work injuries.

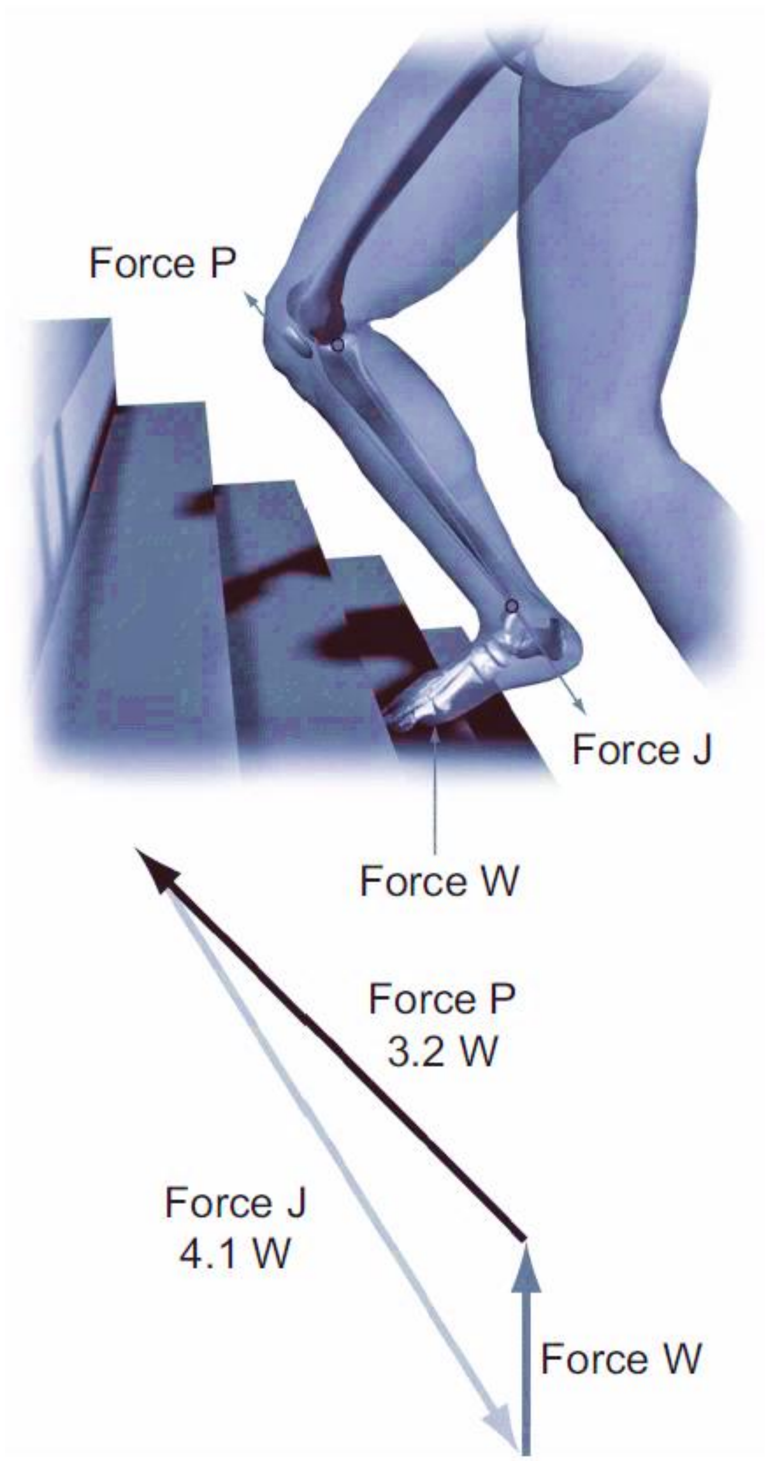

Figure 2.6 An example of dynamic analysis in stair ascent. (Affatato, 2015)

Arthritis can affect a single joint at a time, i.e. a monoarticular clinical manifestation known as monoarthritis, or it may be part of an oligo- or polyarticular disease, affecting less or more than four joints during the first six months of the manifestation, respectively. There are over a hundred different types of arthritis (Schweizer et al., 2014); the most common of them can be classified into the following categories:

1. Degenerative arthritis, also known as osteoarthritis (OA)
2. Arthritis caused by crystal deposition
3. Rheumatoid arthritis (RA)
4. Seronegative arthritis
5. Connective tissue disorders
6. Infective
7. Arthritis caused by metabolic and systemic diseases

Pain is indisputably the predominant symptom of OA of the knee (**Figure 2.7**), and it is commonly restricted to one or both joints. The cause of pain is uncertain; most likely pain originates from the sub-chondral bone, the synovium, menisci and ligaments. Calcium deposits may also cause pain originating from the joint. Pain is present in both active and passive motion, while swelling and muscle atrophy is more apparent in advanced or chronic cases.

Treating knee OA begins with the correct diagnosis of the condition: swelling and pain of the knee might be of a mechanical, inflammatory, neuropathic or psychosomatic origin. Unlike inflammatory pain which is present at night, mechanical pain occurs when the knee is used while less pain is present during resting. Psychosomatic pain has no typical time or origin distribution. Neuropathic pain is related to damaged innervations.

Assessment of the condition is completed by retrieving history of the pain (i.e. acute or chronic pain, past clinical conditions or trauma). If the pain is labeled as mechanical in nature, the most likely diagnosis in elderly is OA. Further investigations include radiographic imaging. Changes such as wear of the articulating surfaces and bony projections, also known as osteophytes, that are formed at the periphery of the joint are common sights found in the imaging of the bones.

Figure 2.7 Normal knee (left) and Osteoarthritic knee (right) (Bellemans J., 2005).

Nonpharmacologic approach for the management of knee OA embraces patient education, aerobic and aquatic exercises to restore muscle strength, and weight loss. Medical recommendations focus on treating the pain with pain-relieving drugs and non-steroid anti-inflammatory drugs. Surgical treatments include tissue repair, arthroscopic lavage (i.e. cleaning out blood, fluids or loose debris), unilateral knee arthroplasty, and total knee arthroplasty.

2.5 TOTAL KNEE ARTHROPLASTY

Knee bearings are commonly made up of three parts, two metal components usually fabricated out of a cobalt and chrome alloy, and a polyethylene insert. For the femoral component to be placed, the anterior, posterior, and chamfer cuts of the femur (**Figure 2.8**) need to be prepared. Frequently, for post-cam designs, an additional femoral box cut (**Figure 2.9**) is required.

Figure 2.8 Anterior, posterior, and chamfer cuts of the femur (sportsortho.co.uk, 2017).

Figure 2.9 Femoral box cut (sportsortho.co.uk, 2017).

For the tibial component, the cut is aimed to be perpendicular to the mechanical axis of the joint. This cut is possibly the most significant cut of the operation since it largely affects the flexion and extension gaps (**Figure 2.10**) (Stiehl, 2004). The objective of these cuts is to get equal flexion and extension gaps, in order to assure that the polyethylene piece is firmly fixed throughout the whole range of motion of the joint.

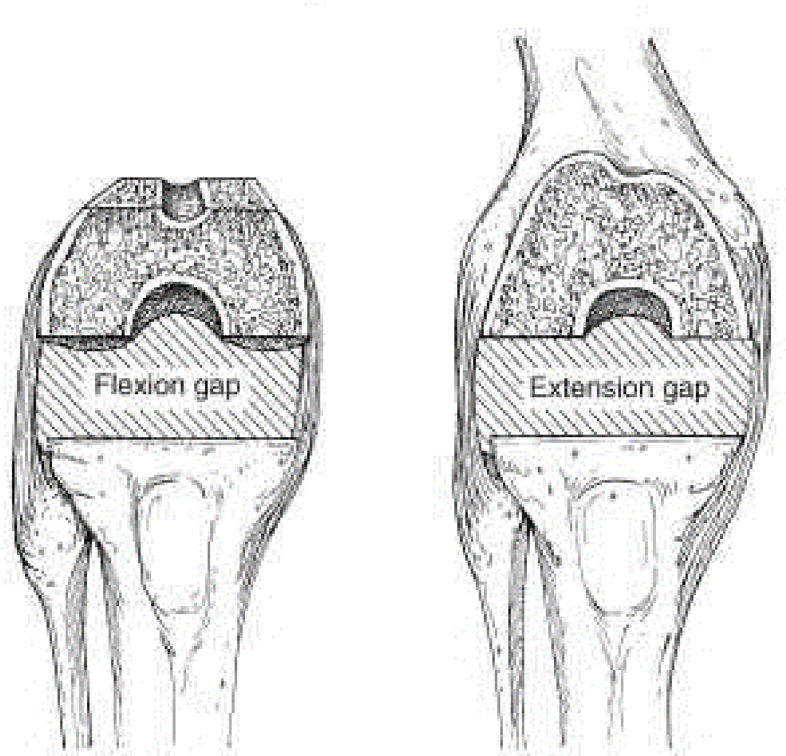

Figure 2.10 Flexion and extension gaps (Yasgur et al., 2002).

Knee implant designs have been notably refined in the recent past, and they have turned into the most reliable joint prosthesis available (Kurtz et al., 2005). The goal of TKA is to elevate pain and re-establish close-to-normal knee function and mobility. It is in fact accepted widely, as the most efficient treatment for end-stage osteoarthritis. Total knee arthroplasty is characterized by very small revision rate of approximately 4.4% after 11 years follow-up (Lutzner et al., 2011). Yet, knee implants have to meet a series of standards in order to guarantee the clinical success of the operation (Affatato, 2015):

- ➢ Anatomical
  - ✓ Restore range of motion
  - ✓ Provide stability

    - ✓ Avert dislocations
    - ✓ Allow minimal bone cuts
    - ✓ Efficient fixation
- ➢ Mechanical
    - ✓ Good and homogeneous stress distribution
    - ✓ Minimal wear and tear, and wear particles
    - ✓ Biocompatible
    - ✓ Wide range of sizes and geometries for individualised needs
    - ✓ Relative low cost

2.5.1 Implant fixation

Fixation of the components to the bone can either be cemented with fast curing bone cements (polymethylmethacrylate), uncemented where the components are press-fitted onto the bone, or with a hybrid fixation. A cemented TKA exhibits a firm and durable coupling between the implant, the cement and the bone (**Figure 2.11**). Yet, over time the cement may crack and wear out; as a result, loosening between the cement and the adjacent bone may occur, causing pain due to the cement rubbing and eroding the bone. Even though this phenomenon is far more common with the prostheses of the hip, 0.6% of TKA patients require a revision surgery due to mechanical loosening (Stein and Taylor, 2004). Cemented fixation is normally endorsed for the elderly or the obese.

Even though cemented fixation was thought to be far more robust than uncemented, there is no evident difference in the longevity and complication rate of the operation (Abdulkarim et al., 2013). Uncemented fixation implants display semi-porous surfaces that allow bone ingrowth, forming a compact attachment to the underlying bone. Cementless fixation (**Figure 2.12**) has the benefit of bone conservation, ease of revision surgery, and avoidance of cementation complications (Akan et al., 2013). Another benefit of using an uncemented prosthesis is the shortened operation time. Cementation errors can cause pain, impingement, dislocation and wear of the knee, and ultimately lead to revision (Akan et al., 2013).

Yet, uncemented fixation is not as secure as cemented, while excessive loading is typically avoided until bone ingrowth occurs. What is more, the cost of cementless TKA is approximately three times more expensive than the cost of cemented TKA in the UK market, due to the cost of bioactive surfaces (Matassi et al., 2013). Uncemented fixation is commonly recommended for younger patients, since the ability of the bone to grow and form a steady connection with the implant declines with aging.

Figure 2.11 Cemented fixation in a 55-year-old male patient (Bergschmidt et al., 2011).

In hybrid fixation, the femoral component is press-fitted (usually along with screws and pegs), while the tibia component is fitted with cement. Cement-less and hybrid implants are today more common than cemented, and they are typically offered in younger and more active patients.

Figure 2.12 Cementless fixation in a 73-year-old female patient (Bergschmidt et al., 2011).

2.5.2 Total and unicopartmental knee prostheses

Knee bearing designs are categorized into unicompartmental (also called “partial”) and total knee prostheses (**Figure 2.13**). Unicompartmental knee implants are frequently used for patients whose damaged bone tissue is limited to a single femoral condyle. Partial knee prostheses are characterised by faster recovery, less pain, and reduced blood loss (Affatato, 2015). Yet, a revision surgery in the case of development of OA in the other areas of the knee is quite common.

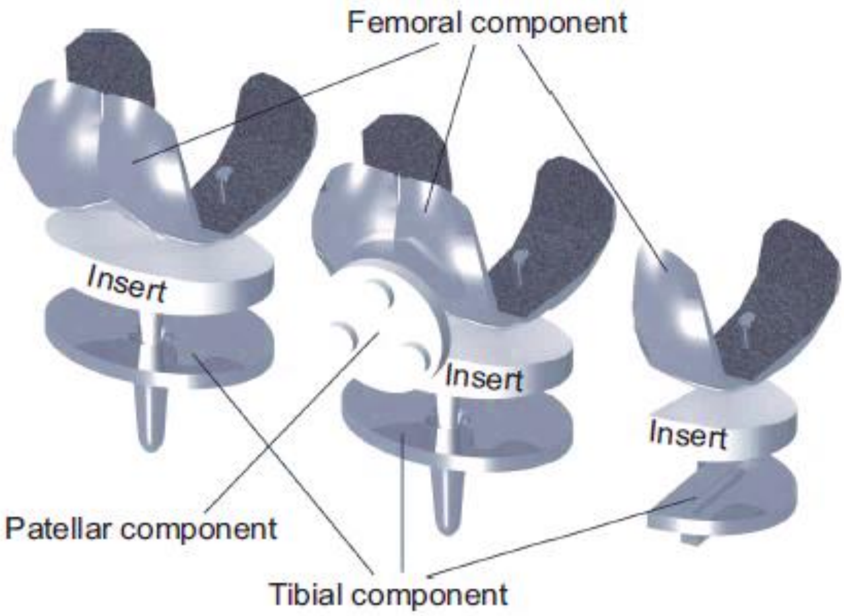

Figure 2.13 From left to right: total, tricompartmental, and unicompartmental knee prostheses (Affatato, 2015)

In total knee arthroplasty, the entire articulation area of both the femur and tibia is removed, and replaced by a femoral and a tibial component. Total prostheses have a femoral component that mimics the asymmetrical shape of the bone, and a tibial flat component that is typically fixed through a short stem in the bone. In this kind of arthroplasty, resurfacing of the patella, or even implanting a patellar component (i.e. tricompartmental knee replacement, **Figure 2.13**) is common practice (Affatato, 2015). Even though authors still debate (Campbell et al., 2006), many surgeons support that resurfacing of the patella (Kolettis and Stern, 1992) and tricompartmental surgeries (Tierney et al., 1994) offer higher estimates of pain relief, better functional improvement, and a smaller chance of post-surgery infection.

2.5.3 Fixed and rotating bearings

Another way to classify TKA designs involves whether the polyethylene sheet is fixed upon the underlying tibial component or whether the insert can rotate short distances inside the metal tibial tray (**Figure 2.14**). These two designs are respectively referred to as fixed and rotating (or mobile) bearings. Fixed bearings have provided durable fixation with high success rates; nevertheless, mobile bearings were developed in order to reduce component wear and allow greater range of motion (Ladermann et al., 2008, Ferguson et al., 2014). Despite the theoretical benefits of the mobile bearing designs, studies have failed to demonstrate any significant advantage of the mobile configurations over the fixed ones (Ferguson et al., 2014, Urwin et al., 2014, Farquhar et al., 2009, Ladermann et al., 2008, Catani et al., 2003).

Figure 2.14 The rotating platform of a mobile bearing.

The rotating bearing design theoretically provides closer to normal knee function and better stress distribution (Ladermann et al., 2008, Ferguson et al., 2014). One disadvantage of mobile bearings is that they are more depended on the surrounding soft tissues and ligaments to avert dislocations. The most significant complication of the mobile-bearing total knee design is the bearing spinout of the rotating-platform (Denavit and Hartenberg, 1955). This type of dislocation is reported with an incidence frequency of 3.2% (Thornby et al., 2009) and most frequently is associated with a loose flexion gap (**Figure 2.10**), i.e. the space between the posterior coronal cut on the distal femur and the transverse cut on the proximal tibia while knee is in flexion (Dolecka et al., 2015). On the other hand, fixed bearings offer greater balance, and are better suited to knees with damaged posterior cruciate ligaments (PCL substituting designs) (Zatsiorsky, 1998). Typically, rotating platform prostheses are recommended for young or active patients (Zatsiorsky, 1998).

2.5.4 Bearing congruity

One more key design consideration is the level of congruity among the femoral component and the polyethylene insert. High congruent knee bearings, have a high degree of conformity between the femoral section and the bearing surface over a wide range of flexion. The high degree of conformity is usually achieved by a constant sagittal femoral radius (**Figure 2.15**, Left). A fully congruent prosthesis has a theoretical range of motion (ROM) of 120°, and a large contact area between the femoral head and the polyethylene insert, which in theory, lessens the contact forces and reduces polyethylene wear. Such implants are characterized by the attributes of "high congruency, high constraint, low mobility, low contact stress"(Bellemans et al., 2005).

Lower congruency bearings (**Figure 2.15**, Right), maintain a large contact area in the first degrees of flexion; yet, in the high end of the flexion range, the sagittal femoral radius is decreased, improving the knee's ROM. However, this small contact area may increase the wear rate of the bearing material (Attias et al., 2015). The design principle in this case can be summarized as "low congruency, low constraint, high mobility, high contact stress" (Bellemans J., 2005).

Figure 2.15 Single radius, and changing radius femoral curvature design.

2.5.5 Posterior cruciate ligament management

Early knee designs resembled a hinge joint, disregarding the ligaments of the knee while permitting motion in one plane. Recent designs include the posterior-stabilized TKA that sacrifices both cruciate ligaments while substituting for the PCL, and the cruciate-retaining designs that sacrifice the anterior cruciate ligament but retain the PCL (**Figure 2.16**). Studies suggest that there is no significant difference in pain level, range of motion, stability and joint strength between the two designs (Misra et al., 2003). Nevertheless, normal motion relies on the preservation of the cruciate ligaments, and thus, PCL retaining designs may provide closer to normal motion kinematics and proprioception (Parcells and Tria, 2016).

The major disadvantage of the sacrificing type of prosthesis with a post-cam mechanism is the cam jump. In posterior stabilised prostheses with loose flexion gaps, or during hyperextension, the cam can rotate over the post and dislocate. This dislocation is treated performing an anterior drawer manoeuvre or with a revision surgery to address the loose flexion gap (Zatsiorsky, 1998). On the other hand, in PCL retaining prostheses a post-operative PCL injury might lead to excessive instability and finally, to a revision surgery. The major advantage of the PCL retaining TKA is that there is no need for a femoral box cut for a post-cam mechanism, resulting in a bone sparing operation.

Figure 2.16 PCL retaining (left) and post-cam sacrificing (right) designs.

2.6 MOTION ANALYSIS

Currently, the functional differences among different bearing designs are commonly quantified by multidimensional motion analysis methods. There are two types of measuring systems in the market today that are generally used to assess human motion. The first type uses equipment that tracks visually the body position, while the second type uses magnetic instruments to define the location and orientation of the moving body (Richards, 1999). Image-based systems may use passive or active markers. Passive markers reflect light back to the tracking devices whereas active markers generate light themselves.

Image based motion analysis involves the recording of two or more consecutive images, usually produced by a high-speed cameras, generating kinematic information based on the apparent motion in the images. In most applications, the cameras are fixed around a capture volume allowing the processor to track the motion of a moving object.

The objective of human motion analysis is to collect data about the dynamics of the musculoskeletal system throughout the completion of a motor activity.

Principally, recorded motion capture data are related to the movement of the entire human body, the relative movement among adjoining bones, the kinematics of joints, the forces acting on the body, the loads acting across tissues and limbs, and the energy and power variation during body performance. The 3-D depiction of the motion of the human movement as observed by any point of view, is a utility addition that motion capture provides (**Figure 2.17**). Such kinematic and kinetic output is either measured or assessed using mathematical models (Cappozzo et al., 2005). In this manner, quantitative information of the human functionality is obtained.

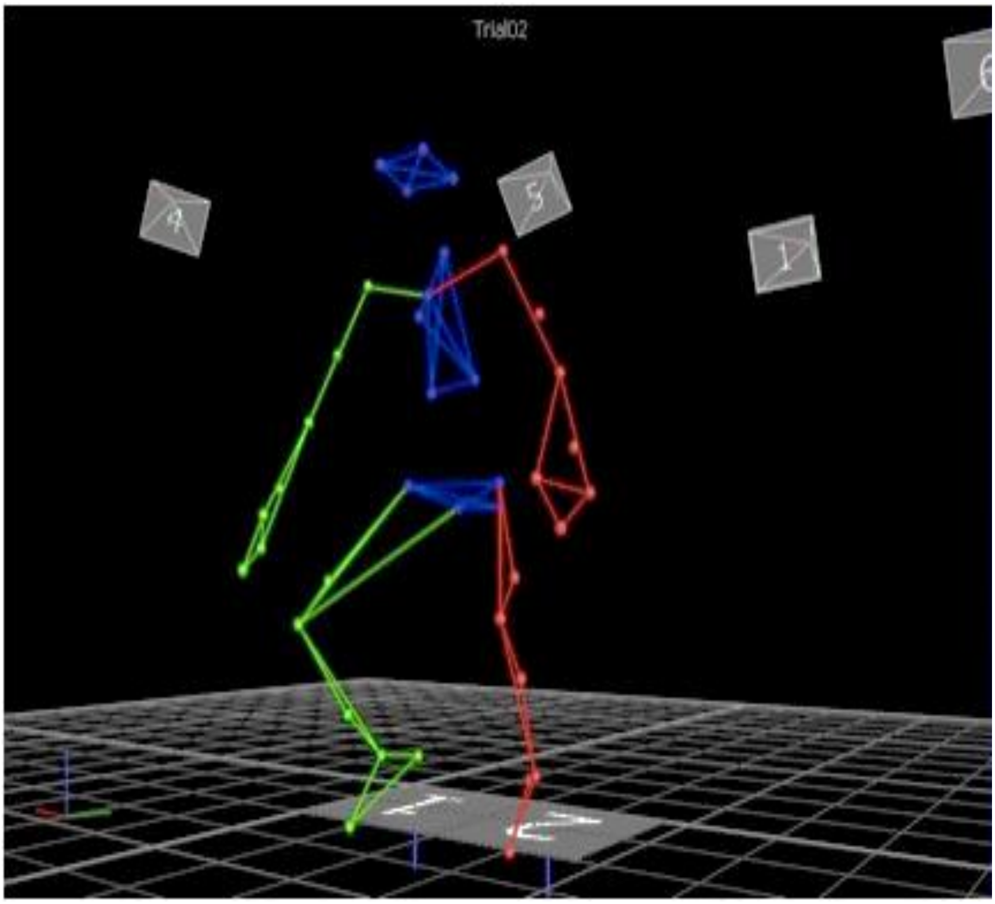

Figure 2.17 3-D depiction of motion trial in Vicon Nexus.

Motion analysis systems that automatically track skin markers are increasingly used by academics and clinicians alike. Even though these systems are many times more accurate than video analysis systems, they are more expensive, are technically complicated, require expert operators, and currently cannot be used outdoors during daylight hours (Bartlett, 2007). Usually, real time locations of markers attached on the skin are obtained by means of motion capture either with conventional photography or with optoelectronic devices. Forces acting on the human body are obtained with the use of force plates. Muscle activity is measured by means of electromyography. Anthropometric measurements are gathered either using measuring tapes or callipers.

In order to access and acquire data that are not directly observed, a biomechanical model of the human body is used. In such models, each body segment is represented by a kinematic chain of links. These segments consist of bones and soft tissues, and as long as a single bone per segment is concerned, they are treated as non-deformable rigid bodies. Joints with up to five DOF link these segments. The sum of segments and joints contribute to the total DOF of the biomechanical model and its efficiency to portray human behaviour.

Segments' soft tissues may or may not be treated as deformable. In most cases, the entirety of the body's segment is treated as a rigid body resulting in a more upfront type of analysis. Yet, authors recently investigated the laws that govern soft tissue movement in order to be included in human movement analysis (Page et al., 2014, Andersen et al., 2012). It is suggested that by disregarding the deformability of such tissues, errors that oppose the applied usability of the results occur (Chèze et al., 1995). Added concerns arise from the inertial effects of wobbling tissue masses that may alter movement dynamics throughout highly accelerated activities (Hatze, 2002).

Segments' kinematic analysis deals with the acquisition of numerical data that permits the reconstruction of a body, in each time frame throughout the execution of an activity. For this to happen, numerical and morphological information is required. The morphological portrayal of a segment is obtained by representing it as a group of elements in relation to an orthogonal set of axes known as local frame. Given this local frame and a second global one, we may calculate the position vectors of the particles of any given segment. This is also known as vector transformation (**Figure 2.18**). The global set of axes may be determined in advance by each researcher by using a wand with fixed markers (i.e. a calibration wand). In a similar manner, it is possible to observe the segment from any possible point of perspective, and thus allowing the 3-D representation of the segment. This approach may be used to describe the segment movement altogether.

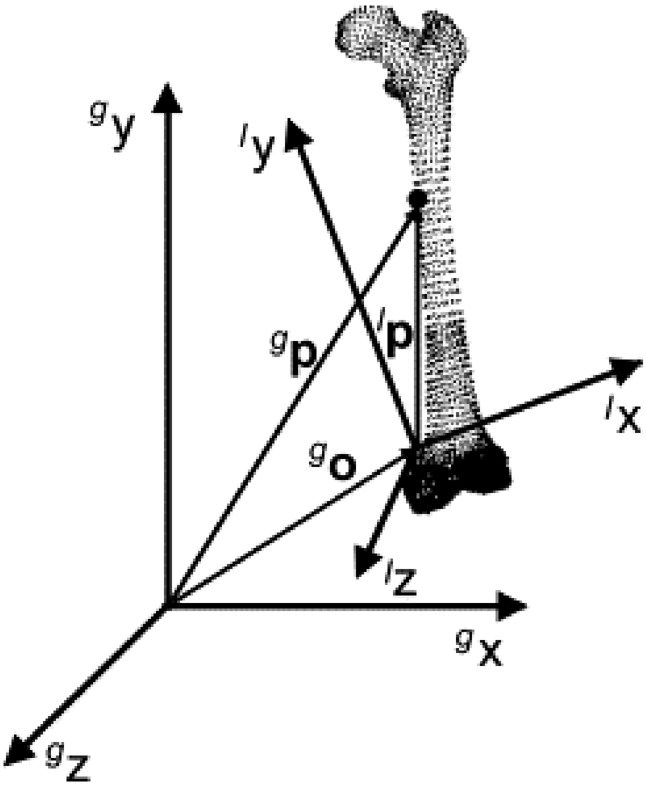

Figure 2.18 Position vector of a particle shown in a global and local frame (Cappozzo et al., 2005).

Usually, three or more markers are required to capture the orientation of a segment. In order to ensure good visibility of the markers at all times, a sufficient number of motion capture cameras are needed. The position of the marker can be arbitrary. Nevertheless, marker position may coincide with anatomical landmarks so that they be recognisable in a repeatable manner. These anatomical landmarks are typically superficial bony prominences and may be identified with palpation. In case of internal landmarks, their position may be estimated by using superficial positions and predictive models.

In human biomechanics, biomechanical information of the relative motion among two segments, one proximal and one distal, is required. This is referred to as joint kinematics, and describes the orientation and location of one segment relatively to the other. Additionally, the use of force plates and the analysis of ground reaction forces allows the calculation of the kinetic behaviour of the body's limbs.

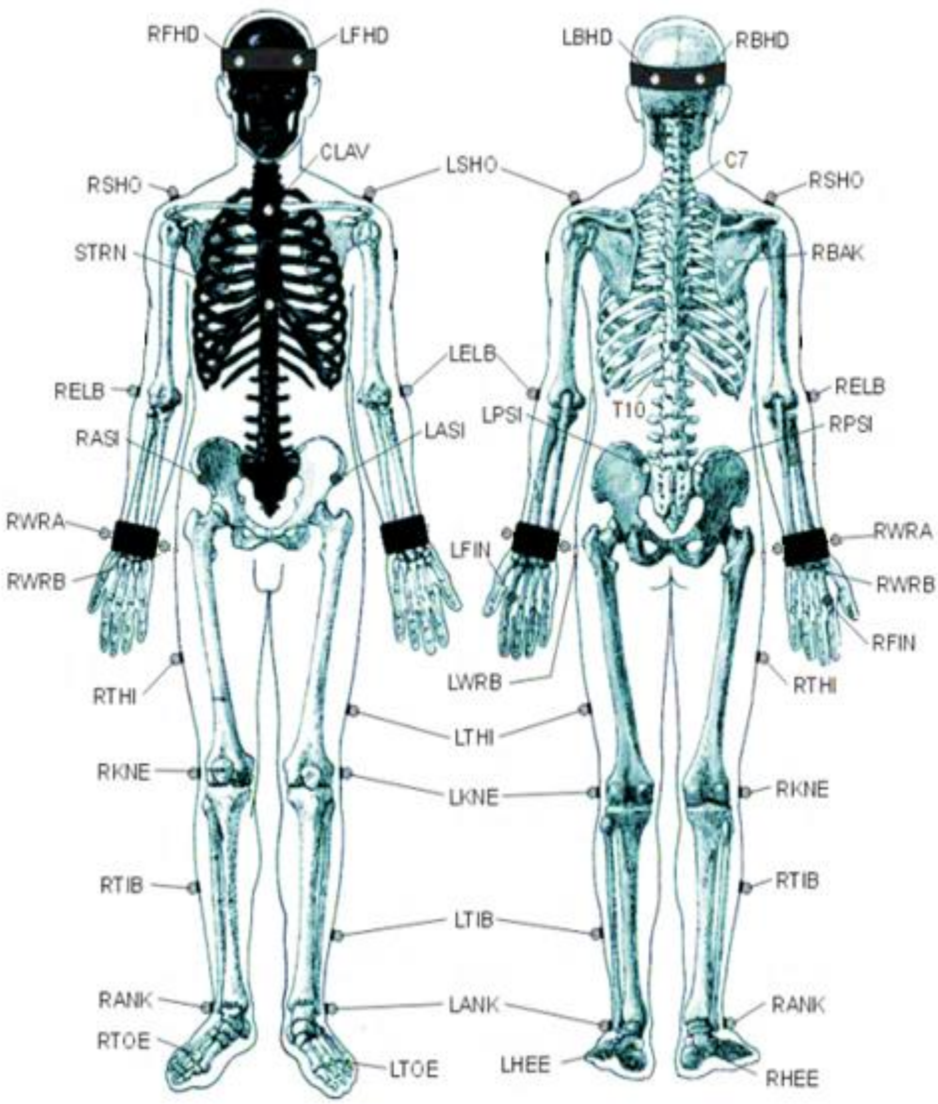

Figure 2.19 Full body PIG, figure (modified) from Vicon (2010).

2.6.1 Plug-in gait biomechanical model

The Plug-in gait (PIG) model is widely used and tested by both clinicians and researchers (Schweizer et al., 2014, Kia et al., 2014, Attias et al., 2015). The following figure and table (**Figure 2.19** and **Table 2.1**) describe in detail where the full-body Plug-in-Gait markers should be placed on a subject.

Table 2.1 Summary of the full-body PIG biomechanical model.

Marker Label	Marker Location	Description
LFHD	Left front head	Located approximately over the left temple
RFHD	Right front head	Located approximately over the right temple
LBHD	Left back head	Placed on the back of the head, roughly in a horizontal plane of the front head markers
RBHD	Right back head	Placed on the back of the head, roughly in a horizontal plane of the front head markers
C7	7th Cervical Vertebrae	Spinous process of the 7th cervical vertebrae
T10	10th Thoracic Vertebrae	Spinous Process of the 10th thoracic vertebrae
CLAV	Clavicle	Jugular Notch where the clavicles meet the sternum
STRN	Sternum	Xiphoid process of the Sternum
RBAK	Right Back	Placed in the middle of the right scapula. This marker has no symmetrical marker on the left side. This asymmetry helps the autolabeling routine determine right from left on the subject
LSHO & RSHO	Left shoulder marker and right shoulder marker	Placed on the Acromio-clavicular joint
LELB & RELB	Left elbow and right elbow	Placed on lateral epicondyle approximating elbow joint axis

LWRA & RWRA	Left and right wrist marker A	Thumb side
LWRB & RWRB	Left and right wrist marker B	Pinkie side
LFIN & RFIN	Left fingers and right fingers	Placed on the dorsum of the hand just below the head of the second metacarpal
LASI	Left ASIS	Placed directly over the left anterior superior iliac spine
RASI	Right ASIS	Placed directly over the right anterior superior iliac spine
LPSI	Left PSIS	Placed directly over the left posterior superior iliac spine
RPSI	Right PSIS	Placed directly over the right posterior superior iliac spine
LKNE & RKNE	Left knee and right knee	Placed on the lateral epicondyle of the knee
LTHI	Left thigh	Place the marker over the lower lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical
RTHI	Right thigh	Place the marker over the lower lateral 2/3 surface of the thigh
LANK & RANK	Left ankle and right ankle	Placed on the lateral malleolus along an imaginary line that passes through the transmalleolar axis
LTIB	Left tibial marker	Similar to the thigh markers, these are placed over the lower 1/3 of the shank to determine the alignment of the ankle flexion axis
RTIB	Right tibial marker	These are placed over the lower 2/3 of the shank

LTOE & RTOE	Left toe and right toe	Placed over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
LHEE & RHEE	Left heel and right heel	Placed on the calcaneus at the same height above the plantar surface of the foot as the toe marker

2.6.2 Errors of motion analysis systems

Apart from the multi inertial measurement unit systems (MIMU), and marker-less methods, most of the human motion analysis techniques are carried out with passive markers attached to the participant's skin. This approach starts with the anatomical calibration process which captures the 3-D pose of the participant's bones. Then, the relative alignment amid adjacent bones is assessed and used to quantify joint kinematics (Di Marco et al., 2017).

Even though motion capture systems are frequently used in research and clinical environment, acquired data suffer from a few sources of error. The inaccuracy of the measurements arises from soft-tissue artefacts (Leardini et al., 2005), markers' misplacement (Della Croce et al., 2005), and instrumental errors (Chiari et al., 2005). The first two errors result from the relative movement between the markers and the underlying tissue and bones, and from the inaccurate marker placement on the anatomical bony landmarks of the body. The third one depends on the number and position of the cameras (Windolf et al., 2014), lens distortion, the size of the capturing volume, and the tracking, reconstruction and calibration procedures used by the system and the operator (Di Marco et al., 2017).

Soft tissue artefact is the most significant source of error in human motion analysis (Andriacchi and Alexander, 2000). It is related to the adopted experimental protocol, effects of inertia, and skin deformation due to body movement (Leardini et al., 2005). It is frequently observed in the skin zones closer to the joints. Due to the nature of the movement, it is often confused with the actual bone movements of the joints, making it very difficult to apply filtering algorithms. The errors associated with the soft tissue artefact are demeaning not only in research projects, but in routine clinical assessments too. Studies suggested different approaches to estimate and cope with soft tissue artefacts (Cheze et al., 1995, Cappozzo et al., 1995, Ball and Pierrynowski, 1998); nevertheless, the results are far from satisfactory (Leardini et al., 2005). To date, to minimise such inaccuracies, the development of more sophisticated joint models is suggested (Leardini et al., 1999). Also, collection of subject specific data to access the soft tissue artefact may be of use.

Figure 2.20 Calibration wand

Studies have also shown that the repeatability and precision of body kinematics is in fact, heavily affected by anatomical landmark misidentification (Della Croce et al., 2005). For instance, miscalculation of the hip joint centre of 3cm due to marker misplacement, may result in 22% error in the calculation of the flexion and extension moments of the hip (Leardini et al., 1999). To minimise such errors, using more than three or four anatomical landmarks per segment, and thorough palpation instructions are suggested (Della Croce et al., 2005).

Finally, regarding the instrumental errors, it was shown that systems with low noise commonly show improved performances (Ehara et al., 1995). It is also recommended by motion capture system manufactures to perform a system calibration before each session. This calibration process is achieved manually by the investigator, who typically swings a wand (**Figure 2.20**) within the capture volume of the laboratory. Different calibration procedures (Di Marco et al., 2017), or even a calibration robot (Windolf et al., 2014) were suggested to cope with calibration uncertainties.

2.7 FUNCTIONAL ASSESSMENTS

Optoelectronic methods are frequently adopted to monitor the rehabilitation progress of patients after total knee arthroplasty, exploring human biomechanics during a series of assessments resembling activities of daily living (Smith et al., 2006, Yoshida et al., 2008, McClelland et al., 2011). Human biomechanics is the study of continuum mechanics (i.e. the study of loads, motion, stress, and strain) and the mechanical effects on the body's movement, size, shape and structure (Lu and Chang, 2012). Human movement is a complicated and rather harmonized mechanical collaboration between bones, muscles, ligaments and joints. From simple to complex, movements are achieved by the muscles producing tensile forces and moments with short lever arms so as to bring stability under the effect of external loadings (Watkins, 2010).

Measuring human motion, constructing 3D computer generated biomechanical models, and calculating internal forces and moments is a common practise for clinical and sports applications alike. Yet, authors rarely investigate the habits and patterns of human movements: Ait El Menceur et al. (2009) and Lempereur et al. (2005) studied the adopted movement strategies during the car ingress movement, whilst Park et al. (2005) examined the movement patterns in stoop and squat lifting motions. To this day, such studies were solely aiming in the simulation of complex realistic movements in the use of computer generated manikins for industrial ergonomic purposes and vehicle designs. Nevertheless, such an analysis may be used to detect and evaluate changes in the movement behaviour of patients undergoing complex surgical operations, and provide clinical insight by distinguishing "healthy" from "unhealthy" movement strategies.

2.7.1 Sit-to-walk strategy assessment

The chair rising movement is one of the most physically challenging activities of daily living and is performed more than 50 times per day in healthy adults (Vissers et al., 2011). Motion analysis studies have extensively explored and elucidated the biomechanics that govern the sit-to-stand (STS) motion (Sibella et al., 2003, Roebroeck et al., 1994, Bouchouras et al., 2015, Bowser et al., 2015, Ikeda et al., 1991, Nuzik et al., 1986). Particularly concerning studies that analyse the motion performance of patients before and after TKA, the STS motion is the third most studied activity of daily living; in a review study published in 2015 Komnik et al. (2015), approximately 15% of the revised articles investigate the biomechanics of this task.

Recent studies also described and studied a similar, but clearly distinct movement, the sit-to-walk (STW) task. The sit-to-walk is a frequently performed activity of daily living that involves the harmonisation of momentum generation and balance control. It is a single continuous motion (Kerr et al., 2013), that contains parts of both the STS and gait initiation movements (**Figure 2.21**). Nevertheless, it is infrequently utilised as a rehabilitation task in individuals with motor impairment, seemingly due to its higher complexity (Chen and Chou, 2013).

Although comparable in nature, studies offer indications of clear differences between the two movements; the STW movement is proven to be more challenging than the STS in terms of maintaining body stability, while bestowing higher falling risks (Schenkman et al., 1990, Kerr et al., 2004). Comparison of the two activities, also reveals that the STW movement is shorter in duration than the STS, due a more rapid gait initiation (Magnan et al., 1996).

Since rising from a chair has been regarded as a perquisite of gait (Schenkman et al., 1990), it is hypothesised that the STW movement depicts a more natural movement when rising from the seated position. What is more, due to its increased mechanical demands, it is assumed that the biomechanical analysis of the activity will better reflect the difficulties experienced by subjects with pathologies of the lower limbs. Finally, the increased demands of this movement will likely reveal more complex and variable ways to complete the chair rising task, i.e. movement strategies.

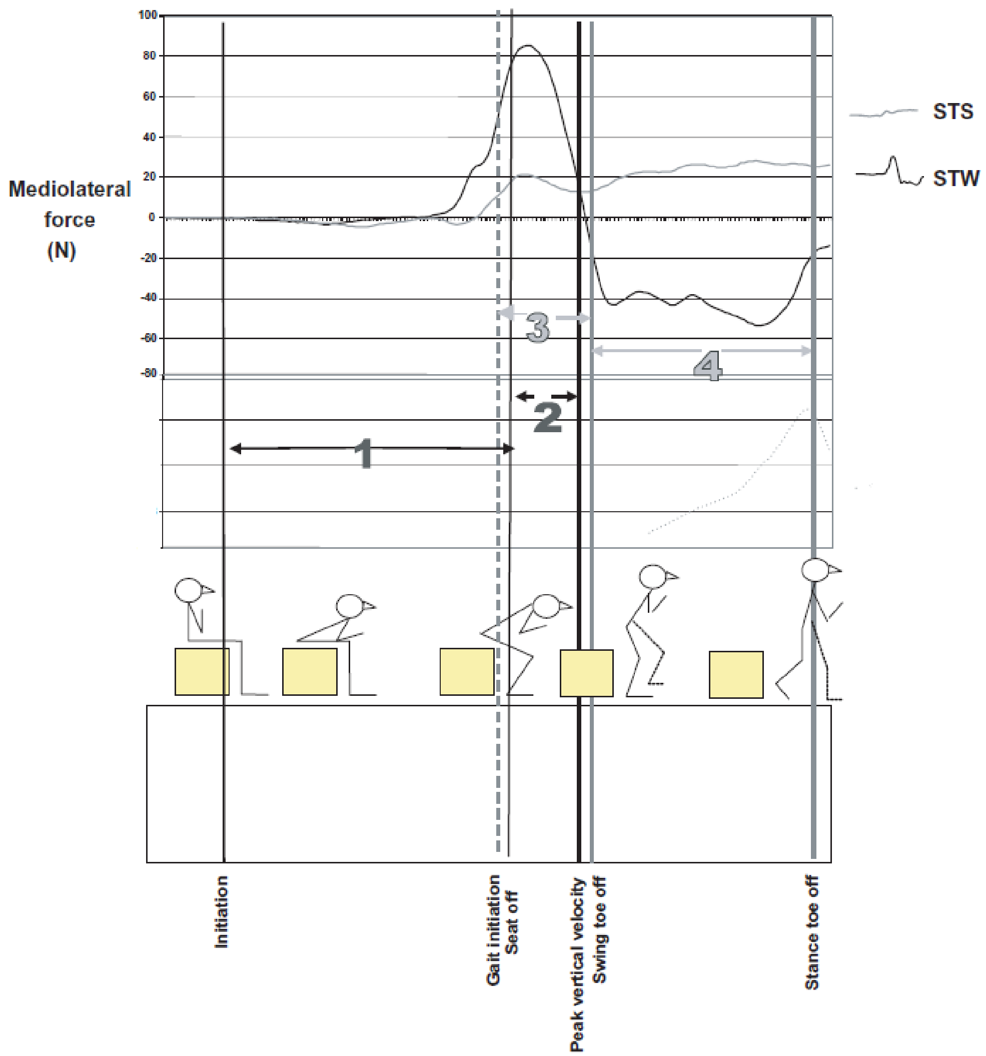

Figure 2.21 Phases of the sit-to-walk movement and their relation to the mediolateral ground reaction force (Kerr et al., 2004).

Movement alterations and neuromuscular adaptations in activities of daily living in patients with knee osteoarthritis are well documented. Studies have reported such changes in level walking (Gustafson et al., 2016, Schmitt et al., 2015, Arnold et al., 2014a), stair ascent and descent (Koyama et al., 2015, Hicks-Little et al., 2012), and sit-to-stand (STS) (Bouchouras et al., 2015, Preece et al., 2015, Anan et al., 2015, Baert et al., 2013, Davidson et al., 2013, Segal et al., 2013, Turcot et al., 2012). The main reason suggested for the movement alterations is to unload the affected joint while keeping the pain experienced to a minimum (Mills et al., 2013, Heiden et al., 2009, Hortobagyi et al., 2005). Yet, such asymmetric adaptations can lead to OA progression, and even knee replacements in the contralateral joints in patients with end-stage OA (Shakoor et al., 2003, McMahon and Block, 2003).

Motor control is an intriguing field of research, exploring the physical and phycological variables that produce diverse, purposeful, and coordinated movements. Latash et al. (2010) and Martin et al. (2009) describe models of movement generation, that include mechanical movement planning (e.g. the directions of an end-effector in space) and neuronal dynamics (e.g. muscle reflex thresholds). Such models, may be used to investigate the brain's physiological variables when controlling muscles, and the neuromotor system's selection of a specific movement from a seemingly endless pool of movement possibilities. Previous authors also mechanistically described human movements and their distinct phases (Dehail et al., 2007, Kerr et al., 2004, Etnyre and Thomas, 2007). Dehail et al. (2007) and Kerr et al. (2004) used kinematic data and GRFs to define 4 phases in the STW movement, whereas Etnyre and Thomas (2007) used vertical GRFs to identify 6 events in the STS movement. Nevertheless, those studies are not delivering descriptive characteristics of the standing movement, but rather use the peak kinematic values and ground reaction forces to spit the task in a sequence of phases. Even though these approaches clearly ease the analysis of the abovementioned tasks by segmenting into phases, movement strategy identification has its own merit: it depicts the motion patterns participants used to complete a movement, while also enclosing information on how subjects interact with the environment. This, can be particularly interesting in the analysis of tasks where the geometry of the environment may significantly affect the output of the measurement (e.g. vehicle types in the car ingress task, or distinct ways to complete the same movement). To put things into perspective, the literature (Janssen et al., 2002) indicates that geometry adjustments in the chair rising task can bring fluctuations of up to 60% in the generated lower limb moments (e.g., a higher chair can lower knee moments by 60%; armrests can influence hip moments by 50%; feet positioning may produce variations in the hip extensor moments of up to 110 Nm).

To date, the identification of movement strategies in the STS and STW movement, or the study of their effects has been achieved via questionnaires, video observation and motion analysis (Dolecka et al., 2015, Sagawa et al., 2013, Gillette and Stevermer, 2012, Bohannon and Corrigan, 2003, Hughes et al., 1994). Pushing through the chair (**Figure 2.22**), pushing through the armrests, pushing through the knees, scooting forward, leaning forward, thorax flexion and obliquity, feet backward, and no arms used, have all been identified as categories of movement strategies (Dolecka et al., 2015, Sagawa et al., 2013, Bohannon and Corrigan, 2003). However, to the authors' knowledge, there are no studies describing numerical tools to identify and classify the standing movement, potentially facilitating rapid analysis of motion analysis data with minimal visual inspection. This, can be an extremely valuable tool when dealing with big motion capture data that need to be analysed to reveal patterns and associations among groups.

2.7.2 Car ingress strategy assessment

Predominantly, motion analysis studies explore level walking, sit-to-stand, stand-to-sit and stair ascent/descent (Komnik et al., 2015). Infrequently more physically demanding movements such as squatting (McClelland et al., 2009), walking followed by a sidestep (Leffler et al., 2012), and obstacle crossing (Mandeville et al., 2008), are investigated in order to uncover compensations mechanisms that may not be apparent in level walking (Komnik et al., 2015, McClelland et al., 2009). Yet, such tasks hardly resemble a so-called "activity of daily living" of elderly people living with knee joint implants.

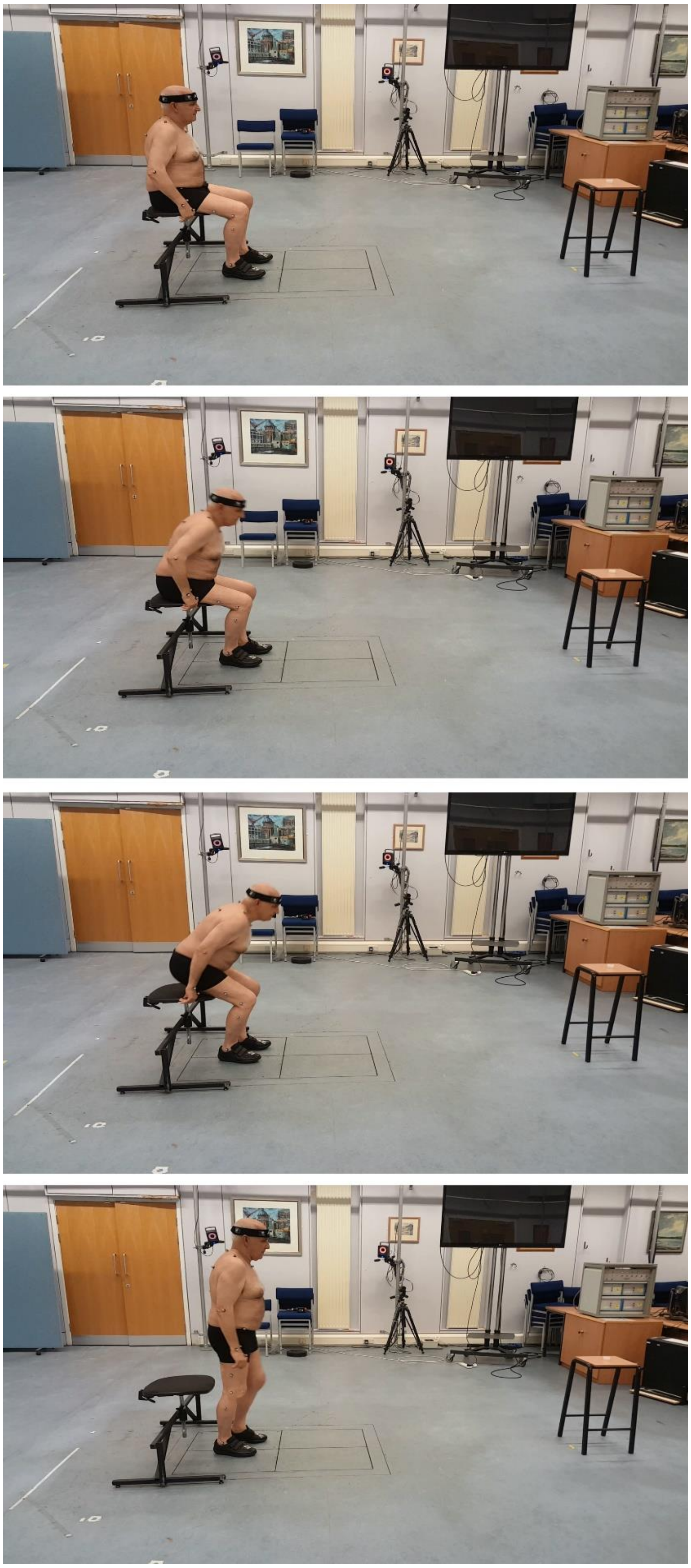

Figure 2.22 The Pushing through the chair strategy for the STW task.

Automobile transportation is vital for both commuting and social interactions, and an inseparable part of today's living requirements. While the interest of the automobile industry in the ergonomical development of vehicles is increasing, biomechanical studies tend to focus on the implications of human motion in vehicle design (Giacomin and Quattrocolo, 1997, Chateauroux and Wang, 2010, Ait El Menceur et al., 2008, Lempereur et al., 2005, Andreoni et al., 2002, Reed and Huang, 2008). What is more, personal transportation in the elderly population is essential for those seeking to preserve an active lifestyle (Lu et al., 2016, Shippen and May, 2016). However, decreased mobility and the ageing musculoskeletal system can precipitate less efficient movement patterns, and ultimately lead to mobility difficulties and dissatisfaction (Daley and Spinks, 2000, Lu et al., 2016). At its very worst, car ingress can lead to serious injuries: in the United States alone, 37,000 people of old age are injured every year when entering a car (Dellinger et al., 2008). In response to that, engineers and medical scientists have begun to study the vehicle ingress and egress movement to investigate how to improve vehicle access (Gish and Vrkljan, 2016). Besides, the importance of the car ingress and egress tasks as challenging activities of daily living in people with OA, is apparent by the inclusion of vehicle accessibility questions in the OKS questionnaire. Based on that, the car ingress task was considered as an important and challenging ADL, and it was deemed as a vital addition to the tasks examined in this study. The car egress task was also considered as an important movement of daily life. Yet, the vehicle ingress is considered to be more challenging: in a study of over 700 elderly people and people with disabilities by the Institute for Consumer Ergonomics in the UK, about half of the participants had difficulties entering the vehicle, whereas only two-thirds had problems getting out (Ergonomics, 1985).

Whilst the comfort and safety of elderly passengers are often addressed and suggestions are offered to enhance their convenience (Petzäll, 1995), populations with prostheses are frequently excluded (Ait El Menceur et al., 2009). However, older people, predominantly those reporting osteoarthritis of the lower limbs, often experience significantly more problems than younger adults, when embarking and disembarking a car (Herriotts, 2005). Thus, this study also focuses on the functional performance of elderly patients with a TKA of the knee in a demanding, but common daily activity, namely car ingress.

The difficulty of the task in question arises from the architecture of the vehicle. Typically, the configuration of the side sill, roof and steering wheel hinders the mobility of the passengers. The interaction of a participant with those elements of the vehicle while performing the movement in a motion caption laboratory, is also the root of complications in the kinematic and kinetic analysis of such recordings. Researchers customarily restrict the movements and habits of the studied population in order to facilitate analysis and allow the comparison of the generated measures: that is, fixing the treadmill's walking speed, using chairs without armrests and staircases without bannisters, dictating the starting position, etc. Nonetheless, vehicle ingress strategies has been shown to feature great diversity in how individuals manoeuvre to get into a car (Ait El Menceur et al., 2009). Thus, restraining the interaction of a subject with the elements of the vehicle may hinder the objectives of the analysis.

Previously, car ingress movement has been investigated through key frame information (Lu et al., 2016) and visual inspection of optoelectronic recordings (Chateauroux and Wang, 2010, Ait El Menceur et al., 2008). Building on the work of Park et al. (2005), clustering methods have also been used to identify several ingress movement strategies (Ait El Menceur et al., 2009, Lempereur et al., 2005, Komaris et al., 2018). One-foot (**Figure 2.23**), two-foot (**Figure 2.24**), trunk forward, lateral sliding and more, were identified as car ingress movement strategies.

Yet, to the authors' knowledge, there are no studies employing movement identification techniques in the TKA population when entering and exiting a vehicle. We propose the examination of the car ingress task through the identification of movement strategies by means of hierarchical clustering. How the adopted ingress strategies vary pre-operationally, post-operationally and one-year post-operationally, is also addressed in this thesis. The proposed procedure may be used to assess post-operative performance of knee implants, and provide insight on the movement habits of patients with knee prostheses, or other knee pathologies, aiding ingress movement simulations and vehicle design.

2.8 OXFORD KNEE SCORE AND QUESTIONNAIRES

Patients report substantial progress in quality of life after TKA, particularly concerning physical pain and mobility (D Fitzgerald et al., 2004). Among self-assessed measures of lower limb function, the Oxford Knee Score (OKS) has good assessment properties, and it is suggested as the best tool for knee replacement that can be applied in large databases (Ko et al., 2009). The OKS contains 12 multiple choice questions on daily activities, which the patient may answer without help from healthcare personnel **(APPENDIX I – Oxford knee score**). Patients tick one of several statements that best describe their joint functional performance. Each question is scored from 1 (normal function) to 5 (extreme difficulty). The global score is the sum of the 12 item scores; therefore, the best possible score is 12 and the worst possible score is 60.

While this survey can effectively capture pain levels and ability to perform certain everyday activities, it relies on subjective opinions. What is more, these tests are not sensitive enough to detect subtle changes in function, or suggest the cause and origin of the pain (Whitehouse et al., 2005, Goldhahn et al., 2017, Jenny and Diesinger, 2012). Versions of OKS have been established in different languages, including the Chinese.

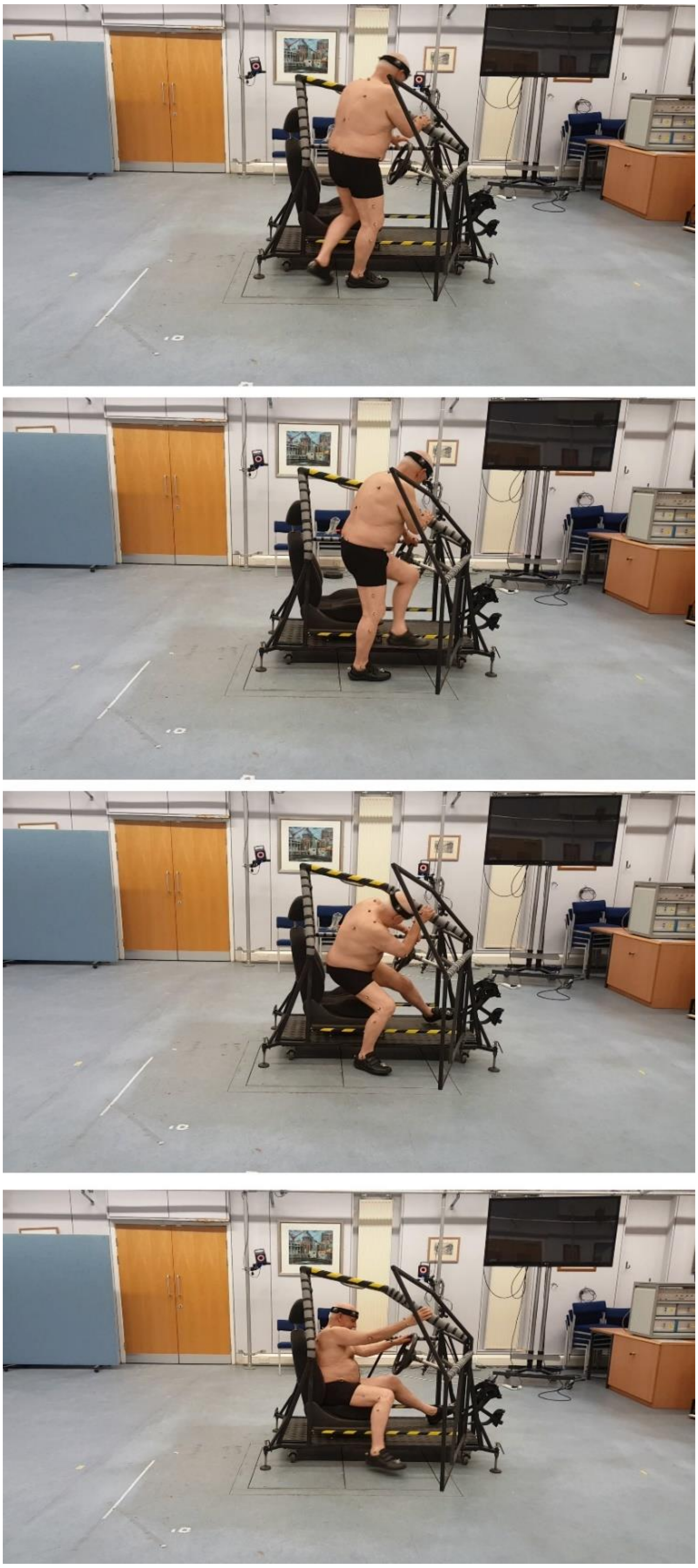

Figure 2.23 The one-foot ingress car strategy.

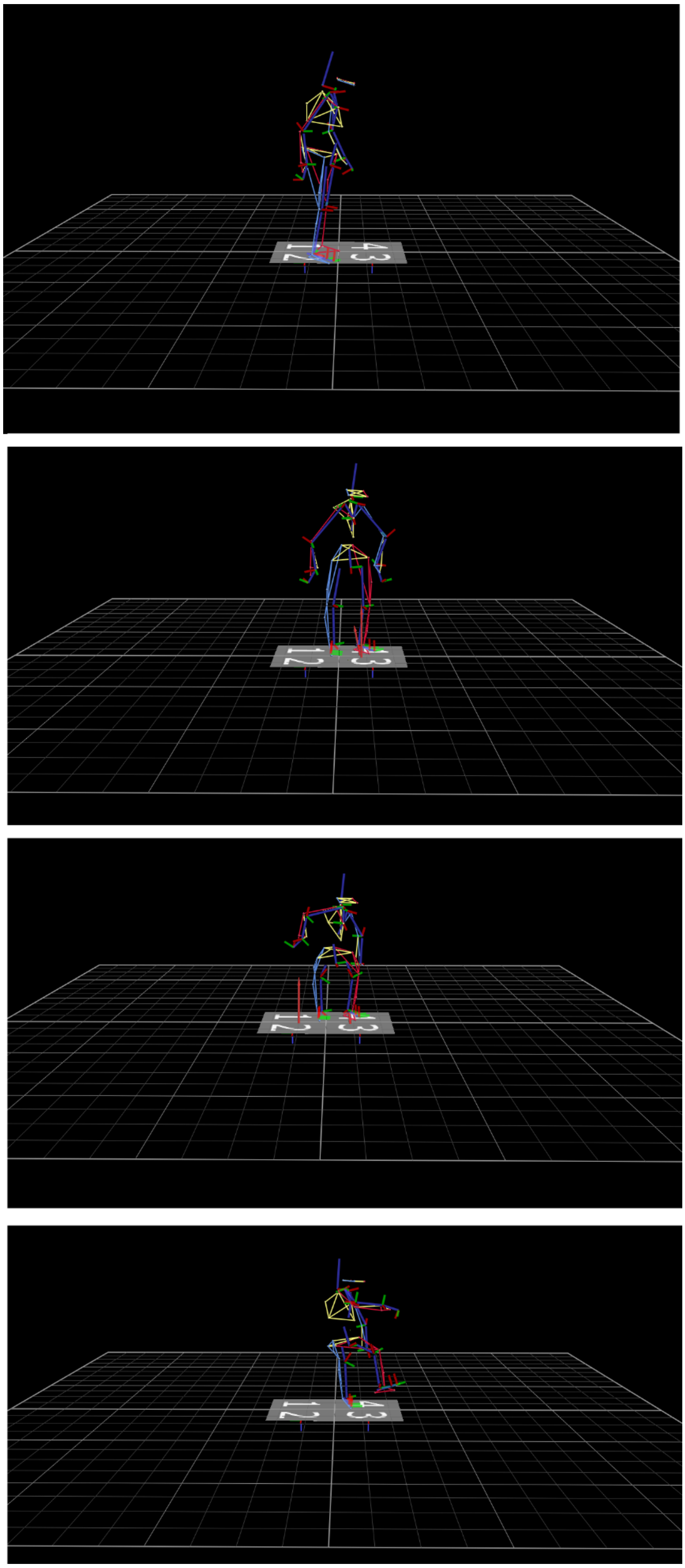

Figure 2.24 The two-foot ingress car strategy.

CHAPTER 3. THE SIT-TO-WALK TASK: A CASE STUDY

This case study will try to identify the key challenges in the biomechanical analysis of the chair rising assessment, and demonstrate the rationale behind a movement identification technique based on statistical calculations, i.e. Hierarchical Clustering. Movement strategy identification is used in this thesis as an assessment tool for the rehabilitation progress of patients with different prostheses of the knee, while welcoming the natural variability of movement patterns in human motions.

3.1 INTRODUCTION

Studies routinely confine the movements of their subjects in order to simplify the analysis and allow the comparison of the produced outcome measures. Starting position and task execution instructions for the chair rising task, are typical examples of this approach: participants are frequently asked to cross and keep their arms on their chest (Abujaber et al., 2015, Spyropoulos et al., 2013), not use their arms to push off the chair (Huffman et al., 2015), keep shoulders at 90˚ of flexion (Sande de Souza et al., 2011), limit feet placement (Spyropoulos et al., 2013), and keep their trunk in a vertical position (Hanawa et al., 2017, Yamasaki and Shimoda, 2016).

Restraints in the starting position and general movement are in contradiction to the recording of an activity of daily living in a so called "natural manner". This restrictive approach may limit even more the efficiency of an assessment involving patients with pathologies of the lower limbs. TKA and OA patients execute everyday tasks in an irregular and asymmetrical manner due to quadriceps weakness and knee joint pain (Anan et al., 2015, Turcot et al., 2012, Sagawa et al., 2013); as a result, confining the execution of the activity may conceal these pathological patterns.

Nevertheless, the variability in the kinematic and kinetic measures of human motion analysis due to the unpredictability and inconsistencies of a person's movements, is indeed strongly prohibitive for comparison purposes. To demonstrate this, three motion capture sit-to-walk (STW) trials of a single participant were analysed. For this case study, no instructions were given regarding the initiation and execution of the task. By doing so, the author hopes to highlight the effect of movement strategy adoption in the biomechanics of a single participant, and the need of an algorithm that will deal with the heterogeneity of movement behaviours, while ideally using it as an outcome measure by identifying healthy and unhealthy movement patterns. It should be noted here, that the terms "healthy" and "unhealthy" are not used in this thesis to label the health of the knee joint, but rather to characterise body movements, where "healthy" patterns are defined by the overall behaviour of the control group.

3.2 PARTICIPANTS

A single adult female participant was considered for this analysis (**Table 3.1**). The participant was recruited via poster and email advertising from the University of Strathclyde population. The volunteer was asked to attend a motion capture session for no longer than 2 hours. The inclusion criteria of this study were: age between 35 and 85, normal body function, and perfect eyesight (with or without visual aid). Exclusion criteria included all musculoskeletal and neurological deficits, previous knee, ankle or hip surgery, and pregnancy. The participant gave written informed consent for the study.

Table 3.1 Participant anthropometrics

Characteristic	
Gender	Female
Weight (kg)	55.8
Height (cm)	169.5
BMI (kg/m^2)	19.4
Age ($years$)	38
Chair height (cm)	49

3.3 DATA COLLECTION

For this case study, a twelve-camera optical infrared system by Vicon (motion systems, Oxford, UK) was used, along with four Kistler piezoelectric based force platforms. The full-body Plug-In Gait model was selected to facilitate the biomechanical analysis. A height adjustable, armless, backless chair was used for the execution of the STW task. For further information regarding the laboratory set-up and the STW protocol, the reader may look at chapters **5.5 Motion capture** and **5.6 The sit-to-walk trials.**

Chair height was adjusted to match the participant's knee height. A table with an everyday object was placed three meters in front of the chair. The participant was asked to comfortably sit on the chair, and on the count to three, to approach the table and grab the object. No other instructions were given. Three successful recordings of the STW task were captured.

The participant in question demonstrated a strong diversity in her movements. During the first recorded trial, the subject adopts a starting position with arms flexed, shoulders abducted and rotated internally, and hands resting on the thighs. The back is straight and upright at this point, while the feet rest almost parallel to each other at shoulder width (**Figure 3.1**, first frame). The participant then initiates movement, characterised by a general flexion of the body, and notably of the torso. Rising from the chair is assisted by the hands that are still in contact with the thighs, and pushing down in order to maintain balance until the seat-off phase of the movement. The right foot is also dragged posteriorly at this point (**Figure 3.1**, second frame). At gait initiation, the right foot swings of the ground, and the hands loose contact with the rest of the body (**Figure 3.1**, fourth frame). During the last phase of the STW trial, the right foot is in the stance phase of the cycle, while the left enters the second swing phase of the gait.

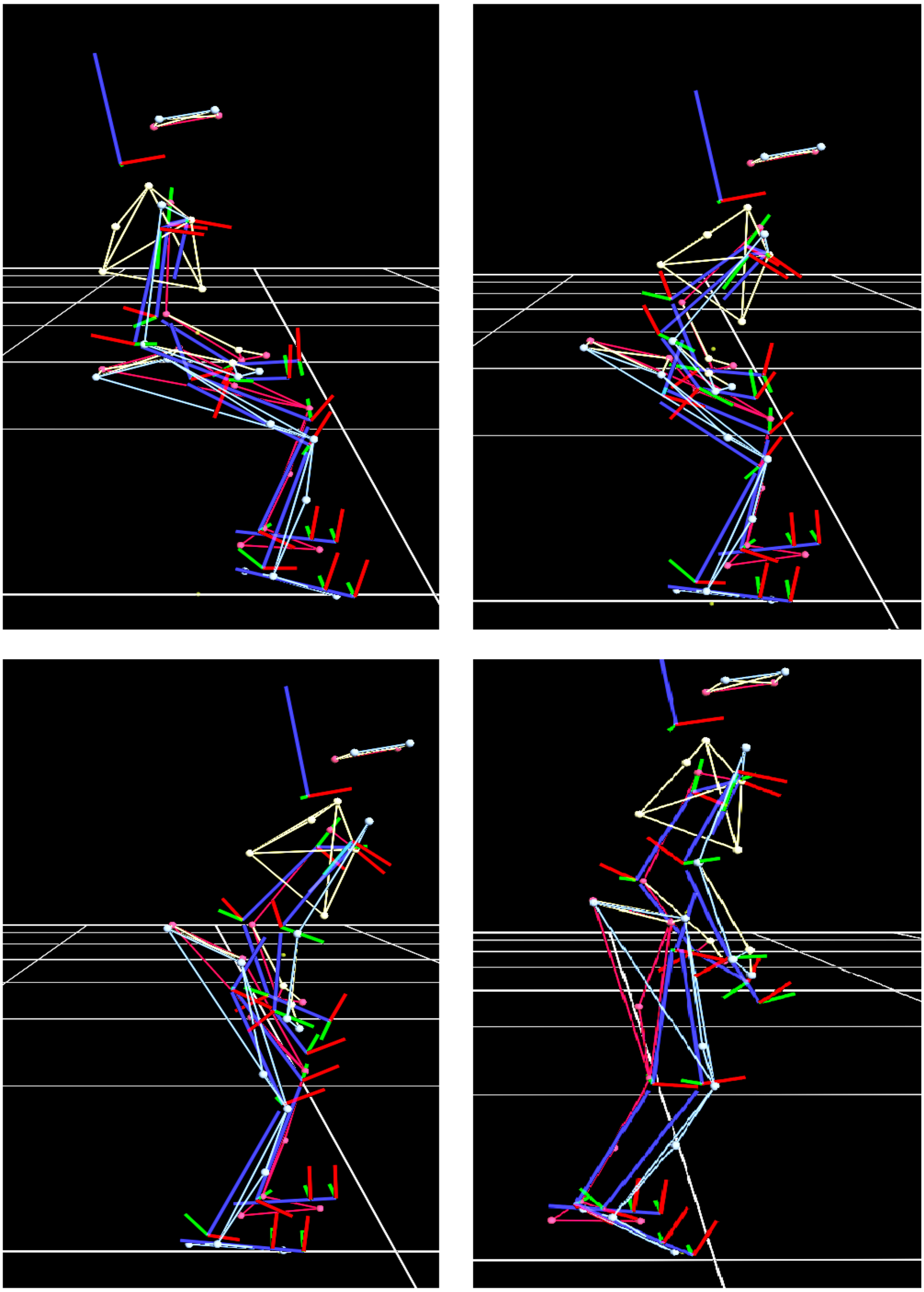

Figure 3.1 STW - Trial 1.

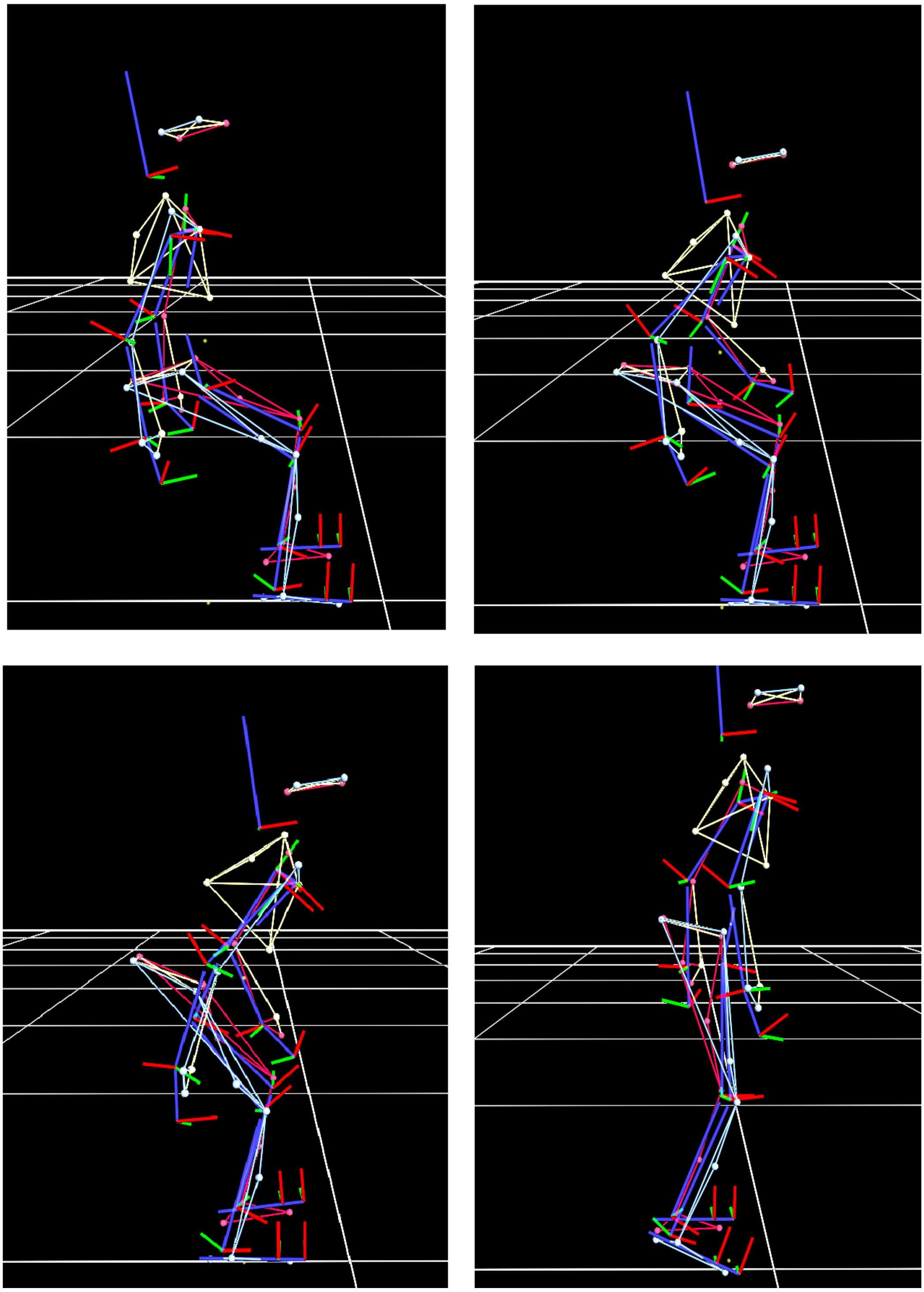

Figure 3.2 STW - Trial 2.

During the second trial, the starting position is similar to the first recording, with the exception of the arms being placed laterally of the torso, while the hands are in contact with the sides and upper surfaces of the chair (**Figure 3.2**, first frame). During the initiation of the movement, the left arm swings forwards, while the right one maintains contact with the right side of the chair until the seat-off phase of the cycle (**Figure 3.2**, second and third frame). Throughout the recording, both feet were stationary until gait initiation. Subsequently, the participant initiated gait with the right foot swinging first.

The body posture in the beginning of the third trial is also similar to the second recording (**Figure 3.3**, first frame). However, in this occasion, both arms are in contact and pushing down the chair during the first instances of the motion (**Figure 3.3**, second frame). Additionally, unlike the first two trials, the left foot is dragged posteriorly (**Figure 3.3**, second frame). Next, the hands loose contact from the chair, and then, contrary to the other recordings, the gait initiation starts with the left foot swinging instead of the right (**Figure 3.3**, fourth frame).

These three trials were analysed, and kinematic and kinetic variables were calculated. Subsequently, those variables were compared with similar findings of control subjects from other studies in the literature investigating the chair rising movement.

3.4 DATA ANALYSIS

This case study reports on three trials of a single participant, executing the STW task with kinematic and kinetic recordings**.** Events were identified from changes and peak values in the recorded data. The start of the STW movement was defined as the instant at which the horizontal COM velocity was higher than 0 ms^{-1} and continued to increase. The end of the STW was defined as the instant where the stance foot is no longer in contact with the force plate (Kerr et al., 2004). The seat-off event was identified in correlation to the local maximum of the anteroposterior ground reaction force (Kralj et al., 1990).

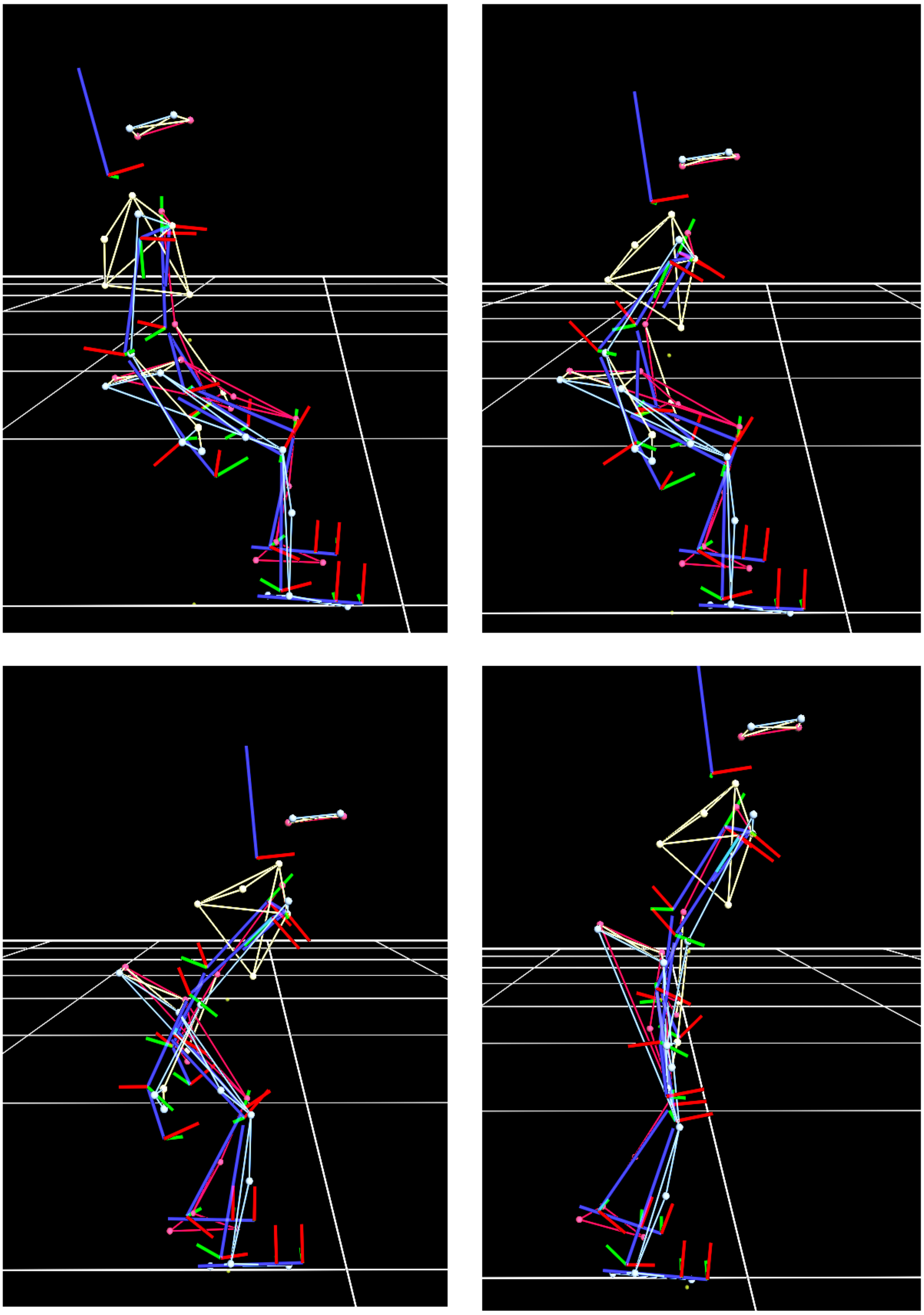

Figure 3.3 STW - Trial 3.

Hip, knee, and ankle moments were calculated by means of conventional inverse dynamics. Hip and knee powers were also calculated. All joint moments and powers were scaled to body weight. Trunk flexion was calculated in the global coordinate system relative to vertical.

Results are compared with the mean values and standard deviations from three different studies with similar analysis (Kerr et al., 2004, Bowser et al., 2015, Lamontagne et al., 2012). All three studies considered control subjects that did not suffer from any former or current serious lower-limb injury or disease. Demographic characteristics were, in most of the occasions, compatible with the anthropometrics of the single participant (henceforth referred to as participant A) whose trials were considered in this chapter (**Table 3.2**).

Table 3.2 Participant A demographics compared to other control populations.

	Age (Years)	Height (cm)	Body Mass (Kg)	BMI (kg/m2)
Participant A	38	169.5	55.8	19.4
(Kerr et al., 2004)	39.8 (12.3)	176.0 (1.0)	80.9 (15.8)	N/A
(Bowser et al., 2015)	42.8 (11.8)	165.5 (7.8)	74.2 (19.5)	26.8 (5.0)
(Lamontagne et al., 2012)	63.5 (4.4)	N/A	N/A	24.9 (3.5)

3.5 RESULTS

Results of the hip, knee and trunk kinematics and kinetics are presented in **Table 3.3**. Recordings 1 to 3 are categorised by sidedness (e.g. left and right hip), where applicable. The last column of **Table 3.3** includes means and standard deviations from control groups of similar studies in the literature. Instead of sidedness, measurements are separated here in dominant and non-dominant sides. It is hypothesised that the non-dominant leg initiates walking, with the first swing of the gait. As a result, in the first two trials of participant A, the left side is considered dominant, whereas in the last trial, the right side is.

On a few occasions, the results obtained in this case study strongly agree with the ones reported in literature: maximum trunk flexion angles (43.7˚, 44.7˚,49.7˚) are within one standard deviation from the corresponding literature reported mean value (41.5˚); as is the trunk angle at seat-off (42.2˚, 44.3˚, 34.4˚ compared to 38.3˚), and the maximum hip extensor moments of the dominant leg (.53, .63, and .75 Nm/Kg, compared to .67 Nm/Kg); similar behaviour is also observed with the maximum hip power on both sides.

Nevertheless, the remaining measures presented in **Table 3.3**, exhibit a strong variability, which is attributed to the adoption of different movement strategies: while in the first two trials the time to seat-off is consistent (.49 and .55 seconds), during the last recorded trial that time was doubled (1.1 seconds) displaying an increase of approximately 10stds; even though the STW time cycle recordings (1.48, 1.70, 2.11 s) are on average (1.76 s) comparable with the literature reported mean value (1.70 s), the highest and lowest values are six standard deviations (.11 s) apart; similar diverse behaviour is observed in all three kinematic and kinetic measurements of the knees: the maximum knee extensor momement and power, and the extension angle at seat-off.

Interestingly, all the literature reported variables show little to no correlation between mean value and sidedness (i.e. dominant and non-dominant leg). For example, the maximum knee extensor moments of the dominant (mean 67 Nm/Kg, std .18 Nm/Kg) and non-dominant (mean 66 Nm/Kg, std .18 Nm/Kg) hip, are rather interchangeable. Similar behaviour can be observed in all the rest literature reported variables of **Table 3.3**. On the other hand, not restricting the execution of the task significantly increased the diversity of the same recordings: extensor moments for participant's A left and right hip, fluctuate from .53 Nm/Kg, to 1.22 Nm/Kg; knee extensor moments from .15 Nm/Kg to .55 Nm/Kg; maximum knee power from .56 W/Kg to 1.39 W/Kg, and so on. Those differences in values among participant's A left and right extremities are up to 3.5 STDs.

Table 3.3 Kinematic and kinetic variables during the STW task, as well as means and standard deviations from control groups of similar studies.

	Participant I						Literature Mean (std)	
	Trial 1		Trial 2		Trial 3			
Max trunk flexion (˚)	43.7		44.7		49.7		41.5 (9.72)a	
Trunk angle at seat-off (˚)	42.2		44.3		34.4		38.3 (8.94)a	
Time to seat-off (s)	.49		.55		1.1		.81 (.06)b	
STW cycle time (s)	1.48		1.70		2.11		1.70 (.11)b	
	Left	Right	Left	Right	Left	Right	D.*	N. D.*
Max hip extensor moment (Nm/Kg)	.53	1.17	.63	1.22	.67	.75	.67 (.18)c	.66 (.18)c
Max hip power (W/Kg)	.76	.74	.74	.82	.76	1.11	.92 (.31)c	.95 (.30)c
Max knee extensor moment (Nm/Kg)	.15	.55	.24	.46	.39	.33	.50 (.22)c	.51 (.13)c
Max knee power (W/Kg)	.56	1.39	.89	1.13	1.25	.57	.88 (.28)c	.87 (.29)c
Knee extension angle at seat-off (˚)	63.0	64.9	80.7	60.5	76.0	69.7	77.7 (6.1)c	78.6 (6.4)c

[a] (Bowser et al., 2015)

[b] (Kerr et al., 2004)

[c] (Lamontagne et al., 2012)

*Dominant and Non-dominant sides.

To demonstrate these differences in the extracted kinetics, the Knee Flexion/Extension Moments (**Figure 3.4** to **Figure 3.6**), and ground reaction force graphs (**Figure 3.7** and **Figure 3.8**) of the three recorded trials of Participant A, are presented below. Although the results from the first two trials are comparable, the knee moments and GRFs for the last recorded trial, show indisputably, a vast difference in body kinetics. Those changes are attributed to the different execution of the task in the third trial compared to the first two recordings, namely the displacement of the left foot (i.e. left foot backwards strategy) and the initiation of the gait with the left leg.

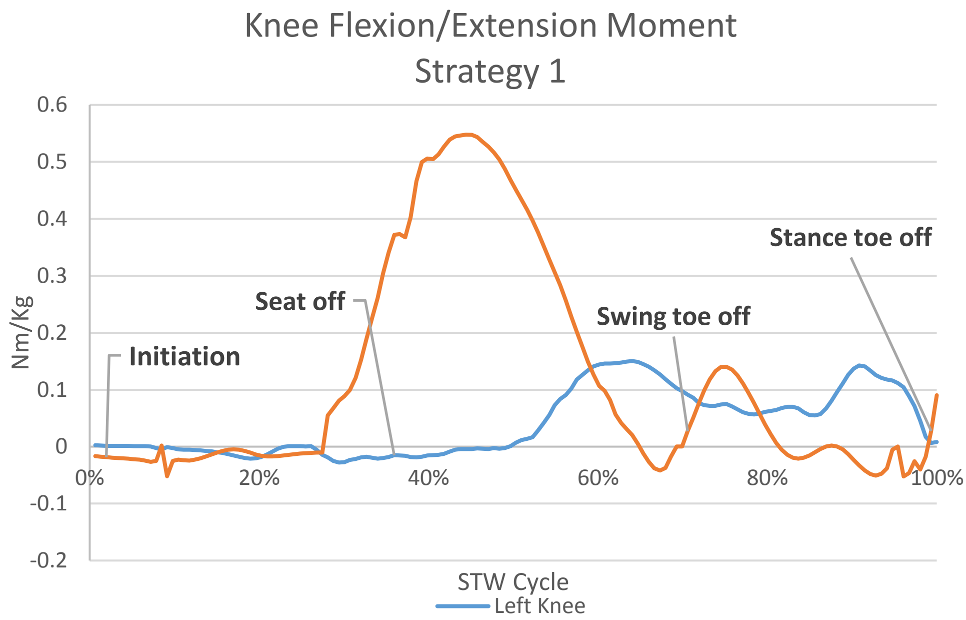

Figure 3.4 Knee Flexion/Extension Moment - Trial 1.

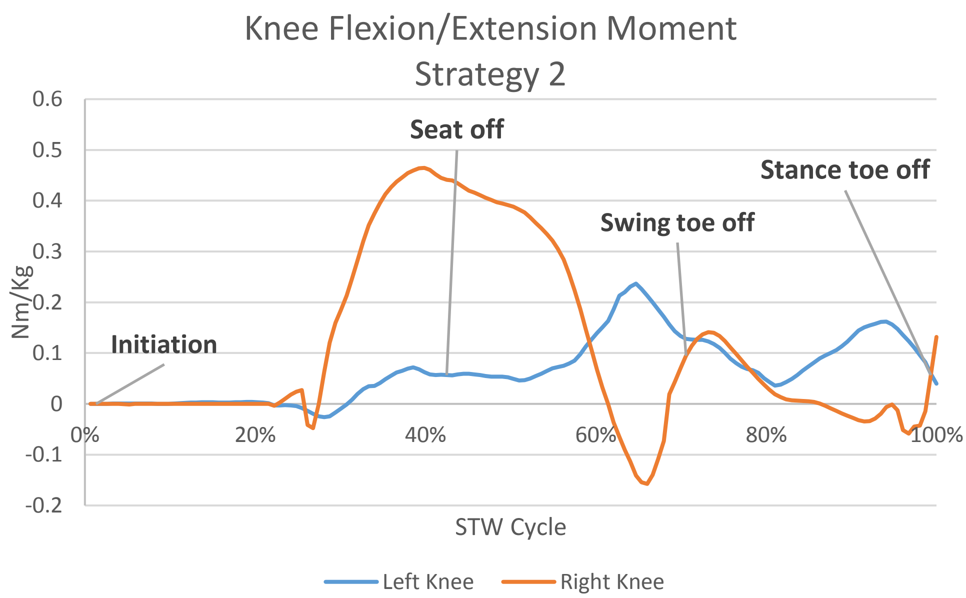

Figure 3.5 Knee Flexion/Extension Moment - Trial 2.

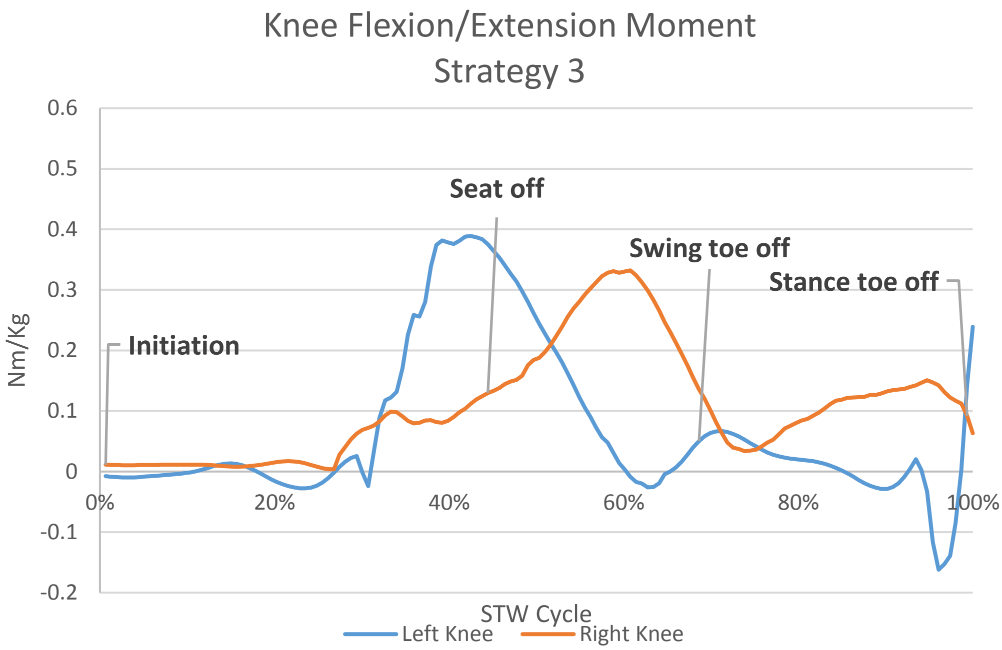

Figure 3.6 Knee Flexion/Extension Moment - Trial 3.

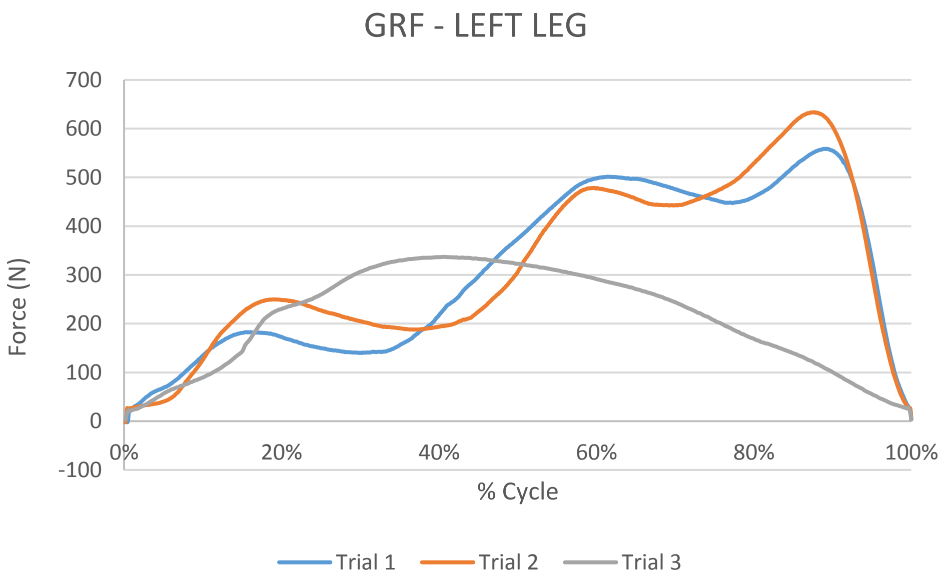

Figure 3.7 Ground reaction forces - Left leg.

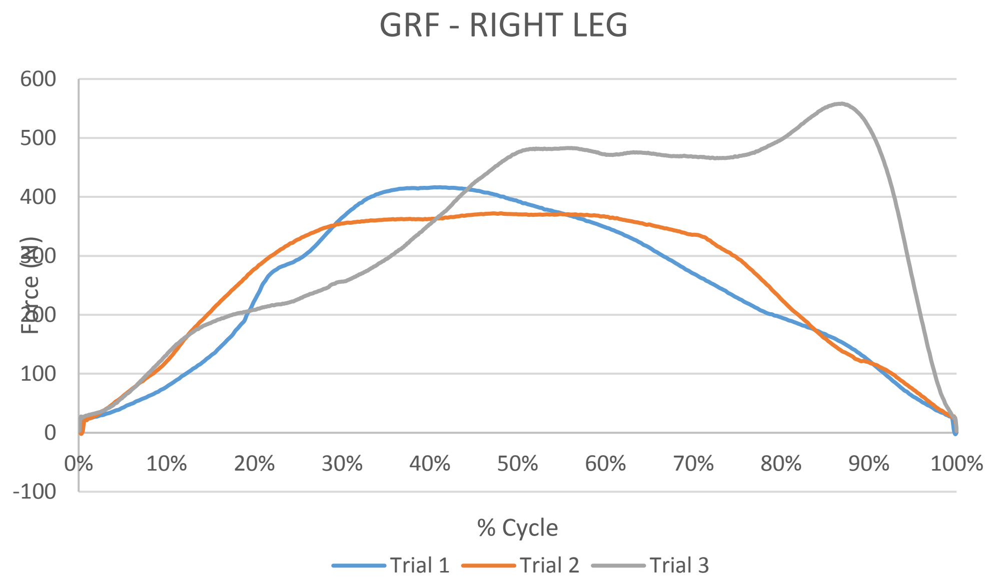

Figure 3.8 Ground reaction forces - Right leg.

3.6 DISCUSSION

Overall, the hypothesis that movement strategies affect the recorded kinematic and kinetic variables was largely supported. Compared to populations of control participants in the literature, the participant considered in this case study exhibits a vast variability in the recorded outcome measures. Even though the mean values of participant's A trials generally coincide with the reported means of the control population (e.g. trunk angle at seat-off, time to seat-off and STW cycle time), the maximum and minimum values can be several standard deviations apart (e.g. time to seat-off and maximum hip extensor movements) (**Table 3.3**). The most notable difference was observed in the times measured until seat-off, and completion of the STW cycle. For the kinetics, the most evident differences among the three tasks were detected for the hip and knee extensor moments, and for the maximum knee power. What is more, contrary to the literature reported population, the kinematic and kinetic measurements of participant's A left and right lower limbs, seem to significantly differ in magnitude (**Table 3.3**).

Our results clearly indicated that performing the STW task in a different manner, can largely affect joint mechanics. It is hypothesised that these variances arise from the different strategies adopted during each trial. It is also assumed that these inconsistencies in a person's movements, may produce results that are unfit for a participant's functional assessment in different time points of his/her treatment. On the other hand, restricting the execution of the task may underwhelm the purpose of an activity of "daily living", or even conceal movement habits crucial for the understanding of the pathology in question. It is also apparent from the three studied trials that postural position at the initiation of the task largely affects the execution of the task. For example, during the first trial of three, the participant kept her hands on her thighs; as a result, during the execution of the STW task, she used her arms to push down her knees. On the other hand, during the last two studied trials, she kept her arms on her sides, and later used them to interact with the sides of the chair. As a result, it is hypothesized that postural start position, and strategy adoption are correlated.

The question posed is whether we could use this natural movement variability to categorise trials based on the strategy each participant used to complete the task. In this case, it may also be possible to identify "healthy" and "unhealthy" movement behaviours based on the controls' and patients' strategy preference. Identifying and classifying certain functional and pathological disorders is a previously discussed topic (Elliott et al., 2009) with undeniable benefits in clinical diagnostics and rehabilitation assessments. Ultimately, this may be used as an assessment tool to access the rehabilitation of the OA patients, by detecting transitions from unhealthy movement patterns, to performances that coincide with the controls' execution.

CHAPTER 4. RESEARCH OBJECTIVES AND STATISTICAL APPROACH

4.1 OBJECTIVES OF THE STUDY

It was demonstrated in the preceding chapter that natural movement inconsistencies are undesirable for the purposes of conventional biomechanical analysis; yet, this variability in movement patterns may offer the perfect breeding ground to establish a technique that could identify transitions in movement behaviour and performance before and after a clinical operation.

As stated in **Section 1.2 Aims of the study**, the key aims of this study are to compare the biomechanical performance of three knee bearings to that of a natural knee, and determine functional improvements postoperatively compared to preoperatively. Due to the wide variation in kinematic approaches to complex functional movement, it is not sufficient to answer this question by analysing joint kinematics and kinetics: this is only appropriate when the same movement is being performed across patient groups. Rather, initially, the movement itself must be described and classified. These classifications can then be compared across groups to ascertain preferential group function, potentially providing insight regarding implant function. To remove subjectivity in the classification process, an automated classification is recommended, which may also remove the need to visually review all cases. To address the project's primary outcomes, we propose the use of a statistical clustering process to classify every-day tasks and detect differences in the movements of people with and without physical disabilities of the lower limbs. The main objectives of the study are as follow:

1. To develop a fast, reliable and repeatable process, build on mathematical calculations, that can cluster and discern healthy form unhealthy movement strategies.

2. To critically compare differences in performance among groups and patient visits with the use of statistical tests such as ANOVAs.
3. To establish that the developed algorithm may be successfully adopted in a range of recordings of different activities of daily living.

In detail, we suggest the use of cluster analysis to classify recordings of people performing every-day tasks. Activities of daily living are recorded by means of motion capture, and further processed in Vicon Nexus (**Chapter 5.5 Motion capture**). The extracted kinematic and kinetic time series are subjected to first and second order decompositions, as described in **Chapters 5.7.4** and **5.6.4: Strategy identification.** The classification algorithm is based on a statistical process called hierarchical clustering. Hierarchical cluster analysis is a statistical technique used to identify structure in a series of objects by organizing the objects into groups, or so called, clusters (Shaw and King, 1992, Warren Liao, 2005). Clustering has been used in a wide range of applications, from the mapping of the brain activity (Golay et al., 1998) to discovering patterns from stock markets (Aghabozorgi and Teh, 2014) and earthquake applications (Shumway, 2003). The concept and process of the hierarchical clustering method is further discussed next in **Section 4.2**. The identification and labeling of the different movement strategies is achieved by observation of a small number of trials on each cluster, as described in **Chapters 5.7.4** and **5.6.4: Strategy identification**. Further statistical analysis is used to determine any differences among the groups in question **(Chapters 6.1 The sit-to-walk assessment** and **6.2 The car ingress** assessment).

In addition to the abovementioned key objectives, this thesis is also concerned with the patient reported satisfaction levels. Clinical outcome questionnaires and the use of the Oxford knee score is addressed in **Section 5.8**, while the results of the analysis are presented in **Section 6.3**, and discussed in **CHAPTER 7**

.

4.2 HIERARCHICAL CLUSTERING

The analysis described in this thesis heavily relies on a statistical procedure called hierarchical clustering. Other techniques such as fuzzy logic (Patrona et al., 2018), deep learning (Wang et al., 2018), and machine learning were previous used to analyse and characterise human motions (Hasnain et al., 2018). Yet, the hierarchical clustering approach was favoured over them in this study for practical reasons: machine learning applications require large data sets, while a part of the studied population is required to train the algorithm (Gareth et al., 2014); as a result, the relatively small sample size in this study makes such algorithms less compelling. On top of that, machine learning algorithms require a priori knowledge of the optimum classification solution, whereas in the hierarchical clustering approach the user is not necessarily familiar with the classification outcome. Finally, fuzzy clustering allows items to be clustered in more than one clusters, which was contradictive to the purposes of this analysis.

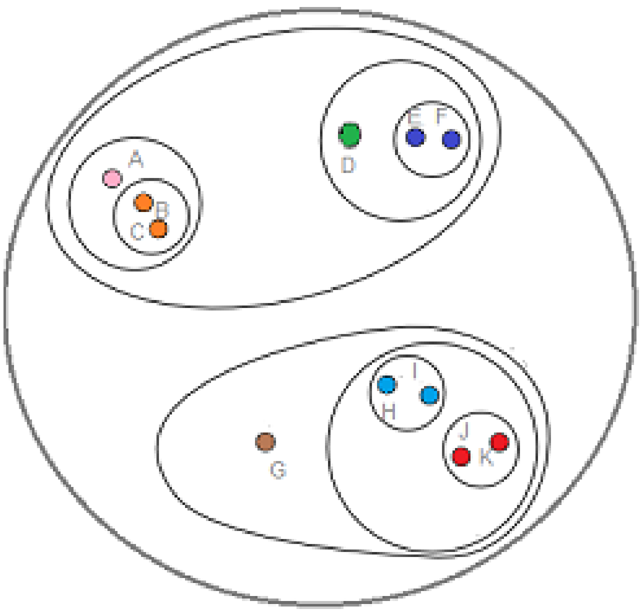

Figure 4.1 Clusters within a population of objects.

This section aims to present a brief but thorough description of the key concepts and mechanics of this method.

Clustering is a statistical method used to form clusters within a population, so that objects in the same cluster are more similar with each other, compared to objects in other clusters (**Figure 4.1**).

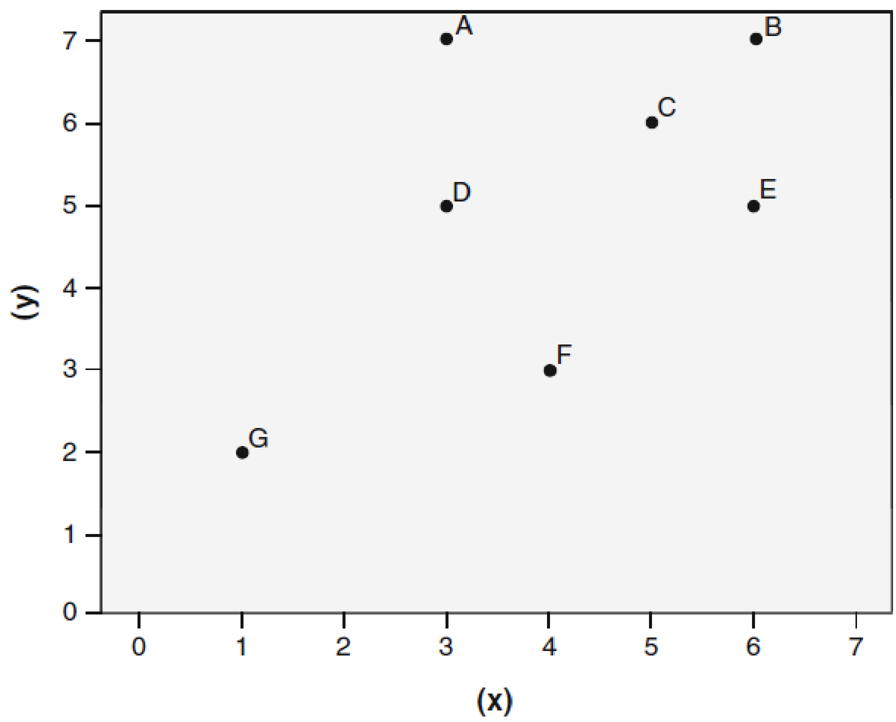

Figure 4.2 Scatter plot of the 2×7 matrix.

The basic input for most clustering applications is a multivariate data matrix $n \times p$ where each row contains multiple measurements describing each object p to be clustered. **Table 4.1** presents an example of such matrix, where G objects are described by two measurements (x and y), resulting in a 2×7 matrix. Given that the seven objects in this example are described by two different measurements, their values can be presented in a scatter plot where each axis signifies one measurement (**Figure 4.2**). Thanks to one of the most impressive and unique cognitive process of the human brain, called pattern recognition, we could possibly tell that the data in this scatterplot may belong in three distinct groups of objects: B-C-E, A-D-F, and G. Nevertheless, such a feat would be impossible if those seven objects were described by more than three measurements, and their depiction in a scatterplot would require a higher order multidimensional space.

Table 4.1 An example of a 2×7 multivariate data matrix.

	Objects						
	A	B	C	D	E	F	G
$Measurement\ x$	3	6	5	3	6	4	1
$Measurement\ y$	7	7	6	5	5	3	2

Hierarchical clustering gets its strength from the concept of multidimensional distance, where a measure of similarity is used to transform the $n \times p$ matrix into an $n \times n$. For example, Euclidian distance used in this work, equally weights distances on all scales. By taking the data in **Table 4.1**, we could compute the Euclidian distance between any two given objects, say A and B, with regards to the two measurements x and y by using the following equation:

Equation 4.A

$$d_{Euclidian}(A, B) = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2} = 3$$

This distance resembles the length of the line between objects A and B. Although in this case only two measurements were used, more than two variables may be considered under the root sign of the equation. Likewise, we can compute the distances between each other pair of objects, and create a distance matrix, the elements of which give a measure of similarity between all objects. In this example, the resulting 8×8 matrix is presented in **Table 4.2**. These matrices are symmetrical since the distance between objects A and B is equal to the distance between B and A. What is more, the main diagonal of the matrix is always equal to zero, since the distance between an object and itself its zero.

Table 4.2 Euclidian distance matrix.

	A	B	C	D	E	F	G
A	0						
B	3	0					
C	2.22	1.41	0				
D	2	3.6	2.23	0			
E	2.82	2.2	1	2	0		
F	4.12	4.47	3.16	2.23	2.23	0	
G	5.38	7	5.65	3.6	5	3.16	0

There are also alternative distance measures such as the:

- city-block distance which uses the sum of the variables' absolute differences,
- the Mahalanobis distance which creates a z-score metric in the multidimensional space such that distances are scaled to the observed variability,
- Pearson correlation which is suitable for qualitative measures, and more.

Values of the $n \times p$ and $n \times n$ matrices may also be transformed allowing procedures such as value standardization (e.g. z-scores or range 0 to 1), or converting an exponential dissimilarity relationship to a linear one (logarithmic transformation).

Next, the technique proceeds to a series of mergers of objects into groups. Initially, each object n, occupies a single cluster. Then, the selected measure of similarity between each and every pair of objects can be used to cluster two objects together resulting in a $n - 1$ cluster solution. The grouping is made on the basis of keeping the within-group dissimilarity at minimum. In the example given, the first merge will cluster objects E and C together.

At this point, the process continues by redefining the distance from the newly formed cluster containing the two objects, to all other objects/clusters. For this, a clustering algorithm (e.g. nearest neighbour, centroid clustering, Ward's method) is used. Differences among clustering algorithms arise from the way the distance (i.e.

similarity) between two groups is defined. The most popular clustering algorithms include the following:

- Single linkage (a.k.a. nearest neighbour): The distance between two clusters corresponds to the shortest distance between any two members in the two clusters.
- Average linkage: The distance between two clusters is defined as the average distance between all pairs of the two clusters' members.
- Centroid: the geometric centre of each cluster is calculated first and the distance between two clusters is equal to the distance between the two centres.
- Ward's method: this clustering algorithm combines those objects whose merger keeps the overall within-cluster variance of distances as small as possible.

Different measures of similarities and hierarchical clustering algorithms may produce very diverse results on the same data set. As addressed by Everitt et al. (2010), apart from general observations regarding the properties of each clustering approach, no recommendations can be made in an absolute sense. Even so, several authors (Gower and Legendre, 1986, Strehl et al., 2000, Huang, 2008) provide a discussion over the choice of the similarity measure given the nature of the data, or provide remarks about typical clustering algorithms (Everitt et al., 2010).

The procedure continues by combining two clusters at each stage until all objects belong in a single cluster. The end product of the hierarchical clustering method is generally depicted as a tree of clusters, known as a dendrogram (**Figure 4.3**) (Warren Liao, 2005). As seen in **Figure 4.3**, and reading from left to right, objects C and E are clustered first. Then A and D follows. Subsequently, object B is combined with the cluster already containing C and E. After that, a new cluster is formed containing F and G. Finally, objects C-E-B-A-D form a single cluster, and shortly after, all objects are combined together. These clustering steps are summarised in **Table 4.3**.

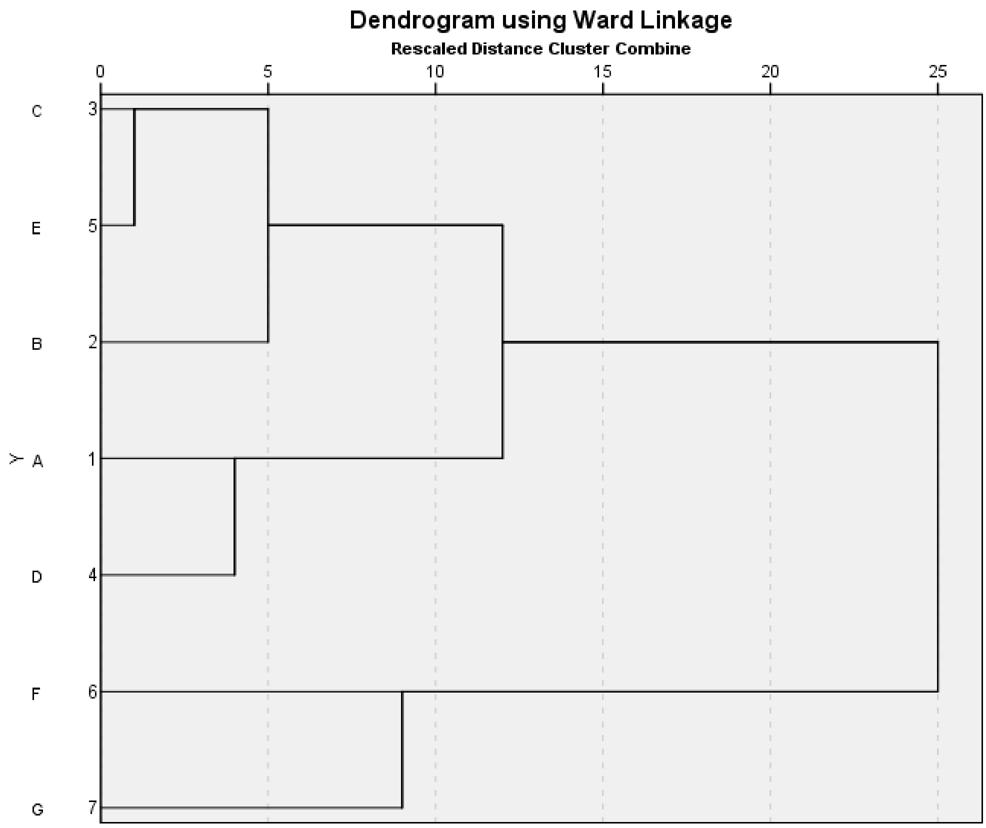

Figure 4.3 A dendrogram.

The most critical issue of the clustering process is determining the number of clusters most representative for the group of objects (Hair et al., 2009). Even though there are no standard techniques, a trend in a measure of dissimilarity, the agglomeration schedule coefficient, can be used as an indicator (horizontal axis, **Figure 4.3**). The agglomeration schedule is a numerical summary of the cluster solution. It is a dimensionless measure, and is usually scaled from 1 to 25. A good cluster solution sees a sudden jump in the distance coefficient. The solution before the gap is likely to be the most satisfactory solution. In this example, the biggest jump in the agglomeration schedule coefficient was observed in the last step of the process, where the cluster containing objects C-E-B-A-D is combined with the cluster containing F and G. In this step, the change in the agglomeration schedule is approximately equal to 12.9 (**Table 4.3**), and thus, a two-cluster solution is indicated. Yet, as addressed by Hair et al, this approach will most often result in a two-cluster solution due to the high increase of the dissimilarity measure when going from a two to a one cluster solution. Occasionally, researchers have a priori knowledge of the optimum number of clusters from previous studies, or a theory to base their decision.

Table 4.3 Clustering steps.

Stage	Cluster Combined		Agglomeration schedule coefficient
	Cluster 1	Cluster 2	
1	C	E	1
2	A	D	3.1
3	CE	B	0.9
4	F	G	3.9
5	CEB	AD	3.2
6	CEBAD	FG	12.9

Unlike clustering of static data, time series clustering can be notably challenging, especially in long time series with dissimilar lengths (Nanopoulos et al., 2001). In those cases, authors have resorted to approaches of capturing the behaviour of the curve by means of first and second-order decompositions, such as mean value, standard deviation and trend, in order to extract the multivariate data matrix $n \times p$ required by the clustering process (Nanopoulos et al., 2001).

Even after determining the optimum number of clusters, the objects of each cluster must be reviewed to ensure that the results are interpretable and meaningful. In this thesis, movement strategies are identified through visual inspection of the motion capture trials prescribed to each cluster. Such a reliable procedure will allow the identification of the strategy attributed to each cluster by visually inspecting only a fraction of the cluster's trials. This, combined with the advantages of a process utilizing quantitative data and statistical methods over observational techniques, will allow the fast and consistent identification of movement strategies in bulky motion analysis data libraries.

CHAPTER 5. METHODOLOGY

5.1 STUDY DESIGN

This project compares three knee prostheses from the Columbus® Knee System range (Aesculap AG, Tuttlingen, Germany) that are currently used in TKA surgery: a high congruent bearing in mobile and fixed configurations, and a low congruent fixed bearing. Adults aged between 35 and 85 were recruited as the control group for the study. Volunteers were asked to attend a session for no longer than 2 hours. The procedure followed in the control and the patient groups is unchanged and it is described in detail in this chapter. Control participants were recruited via posters, flyers and email advertising. The inclusion criteria for the control participants were:

- ✓ Able bodied
- ✓ Normal lower limb function
- ✓ 20/20 vision (with or without visual aid)

The exclusion criteria were:

- × Musculoskeletal, neurological or sensory deficit
- × Those who are, or think that they may be pregnant
- × Previous hip or knee replacement procedure
- × Unable to give written consent
- × Previous ankle surgery

Patients scheduled for total knee arthroplasty, under the care of four consultant orthopaedic surgeons at the Golden Jubilee National Hospital who meet the inclusion/exclusion criteria, were recruited and randomised into one of three study groups. The inclusion criteria for patient participants were:

- ✓ Suitable to have any of the three study implants
- ✓ Over 35 years of age
- ✓ Able to return for follow up sessions

Exclusion criteria:

- × Previous hip or knee replacement in the previous six months
- × Unable to give written consent
- × Previous ankle surgery

Invitation letters and participant information sheets were sent out to suitable patients prior to their preoperative consultation. Patients were approached at their consultation visit and they were given the opportunity to ask questions about the study. Following written consent, recruited patients were randomised using sequentially numbered opaque sealed envelopes. A nominated person, independent of the approach and consent of the patient, signed and opened the envelope and informed the hospital research team of the randomisation. The patient and the university research team were blinded to randomisation. For each patient, arrangements were made for their preoperative movement analysis testing session. Subsequently, they had their surgery and rehabilitation prior to discharge according to standard hospital practice. Participants returned to the hospital for standard follow up appointments at six weeks and one year after the operation. At the same time, arrangements were made for them to attend their follow up movement analysis sessions. Clinical data recorded at preoperative assessment and postoperative follow up appointments, such as range of movement, Oxford Knee scores, patient satisfaction, and radiographic measurements.

Patient participants were asked to attend movement analysis testing sessions at the University of Strathclyde in Glasgow on three separate occasions;

preoperatively, at 48 weeks postoperatively and at one year postoperatively. Each of these sessions followed the same procedure. Prior to data collection, participants (both controls and patients) were asked to change into the provided tight-fitting shorts and vest tops (male participants were asked to forego the vest tops) in the changing rooms within the laboratory facility. Measurements of weight and body dimensions were taken (required for processing the data) and then reflective markers were attached to the legs, pelvis, torso, and arms. These were attached using double-sided toupee tape or elasticated straps as required. Another four markers were attached on their head with a headband. Marker placement, clothing and the calibration posture of a control participant is shown in **Figure 5.1**.

The project presented in this thesis is part of a larger research clinical trial carried out by two student investigators. Five activities of daily living (ADLs) were carried out in two laboratories: the standard motion capture laboratory (S) and the CAREN system laboratory (Motek Medical, Amsterdam, Netherlands) (M). Force plates in the floor of the motion capture laboratories were utilized to record ground reaction forces. The ADLs were:

1. Level walking (S)
2. Sit to walk (S)
3. Ascending and descending stairs (S)
4. Car ingress (S)
5. Walking on an incline (M)

Participants were asked to perform ADLs in a fixed order, and until at least three good sets of data were collected. Instructions on how to perform each ADL prior to recordings were given and subjects were asked to practice them before data collection. During demanding tasks, participants were supported by a harness or hand rails to prevent falls. To minimise any potential pain or discomfort, breaks were scheduled between activities or as requested, for as long as necessary. If a person was unable to complete the activity, the test was stopped. Upon task completion, participants filled in a questionnaire about the difficulty and pain levels experienced while performing the ADL (**APPENDIX III – Sit-to-walk questionnaire** and **APPENDIX**

IV – Car ingress questionnaire). On completion of the test protocol, the markers were removed, the participant changed and was free to leave. Each testing session lasted between 1.5 and 2.5 hours. The work in this thesis deals with the analysis of two tasks, the Sit-to-walk (**5.6 The sit-to-walk trials**) and the Car ingress task (**5.7 The car ingress trials**).

Participant recruitment is still ongoing; up to now, 81 patients and 20 control participants who met the inclusion/exclusion criteria have been recruited and tested at the University of Strathclyde. Recruitment, and the remaining movement analysis testing for all three occasions, will be taking place on the premises of the Golden Jubilee National Hospital, Glasgow, UK.

Figure 5.1 Calibration - A control participant.

5.2 ETHICS

The study was carried out in accordance with the standards of Good Clinical Practice and the Declaration of Helsinki. All members of the research team had up to date GCP training. Approval from a NHS Research Ethics Committee Board 5 and the University Ethics Committee was required prior to the commencement of the study. Separate ethical approval was provided through the University Ethics Committee for the collection of control data since this does not involve NHS patients, staff or premises.

5.3 CONSENT FORMS AND DATA STORAGE

Consent forms form the control group were kept confidential, stored indefinitely (with consent) in a locked cabinet in the Department of Biomedical Engineering (**APPENDIX V – Participant consent form**). If consent was given by the participants, video recordings were taken. Additionally, all the information was saved as a backup in a password protected folder on password protected University of Strathclyde computers and external hard drives. If consent was given all videos will be kept indefinitely.

An ID code links the collected data to each control participant. The code list is stored in a locked cabinet in the Department of Biomedical Engineering. The coded list, consent forms and collected data are only available for those researches named in the departmental ethics application. The code list will be destroyed 5 years after completion of the study and thereby the pseudo-anonymous data will become anonymous.

Data gathered within the hospital for the patient groups will be treated in the same way as clinical records following the NHS code of practice on protecting patient confidentiality (NHS Scotland). Patients agreed to take part in the study were assigned a unique study ID number. All research data collected at the university are stored as anonymised data. Hard copy data are kept in a locked cabinet accessible by members of the research team only. Electronic data collected during the functional testing sessions were stored on a standalone computer with password secured user accounts accessible only by members of the research team. Other study related electronic data were stored on university servers in the personal accounts of research team members and accessible only by that individual by a user name and password. At the university, there is one paper document linking the study ID to participant's name stored in a locked cabinet. No personal data were or will be published.

5.4 SUBJECT REQRUITMENT AND PATIENT GROUPS

Participating patients were randomised to receive one of three different variants of the Columbus® knee prostheses (models: UC, UCR, and CR DD) (**Table 5.1**). Two of these variants (UC and UCR) are ultra-congruent designs, while the last (CR DD) has a lower congruency. Both ultra-congruent variants are posterior stabilised, but the CR DD is a cruciate retaining design. Posterior stabilised designs require the posterior cruciate ligament to be resected. One of the variants, the UCR, is a rotating platform bearing, while the other two are fixed designs. All the implants in the study used cemented fixation on both the femoral and tibia side. Recruited patient participants were treated by four different orthopaedic surgeons. No patient was recruited to the study if randomisation to receive any of the variants would leave him/her clinically or functionally disadvantaged.

Table 5.1 Columbus knee prostheses.

	Knee Bearings		
	UC	CR DD	UCR
High Congruent	✓		✓
Low Congruent		✓	
PCL substituting	✓		✓
PCL retaining		✓	
Rotating platform			✓
Fixed platform	✓	✓	

5.4.1 Fixed high congruent bearings (UC)

The PCL-sacrificing fixed gliding surface of the Columbus® UC is a posterior stabilised variant implant (**Figure 5.2**-Left), but without the need of a femoral box to be prepared for a post-cam mechanism. Since there is no post-cam mechanism in the UC design, no femoral box preparation is required, resulting in a bone sparing and time saving operation. Also, the ventrally flattened meniscus design lowers the risk of patellar impingement. This design offers great balance to a knee with an absent PCL, good range of motion and better polyethylene wear characteristics.

5.4.2 Fixed low congruent bearings (CR DD)

The PCL-retaining fixed gliding surface of the Columbus® CR DD (**Figure 5.2**-right) is designed to offer kinematics closely resembling the normal knee. PCL retaining prostheses are negligibly constrained and highly dependent on the function of an intact posterior cruciate ligament. Similarly to the UC design, a femoral box cut is not required, thus avoiding patellar impingements and post dislocations that might occur in posterior stabilised knees. Since the cruciate ligament is retained, this design also offers enhanced proprioception.

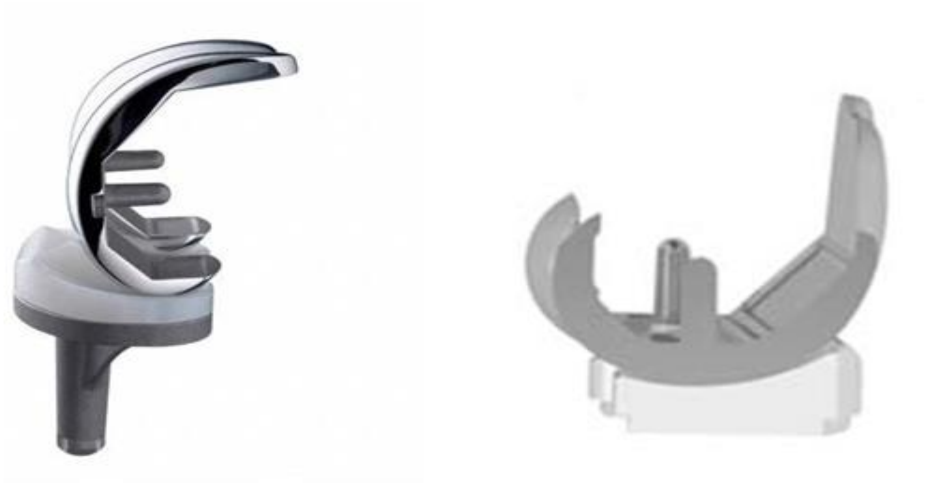

Figure 5.2 The UC (left) and CR DD design (right).

5.4.3 Mobile high congruent bearings (UCR)

The Columbus® UCR knee prosthesis (**Figure 5.3**) enables a rotating gliding surface to be used for PCL resections. This minimally constrained prosthesis allows the polyethylene insert to rotate ±20° on the tibial plate (**Figure 5.4**). Theoretically, the design's increased contact area is reducing the loading on the meniscus insert, minimizing polyethylene wear to under 1 mg per million cycles. The tibial overhang due to the rotational movement of the polyethylene insert is limited to A=3.6mm and B=0.8mm for 20° of motion, and thus diminishing the risk of any adverse impingement.

Figure 5.3 The PCL-sacrificing rotating gliding surface Columbus® UC.

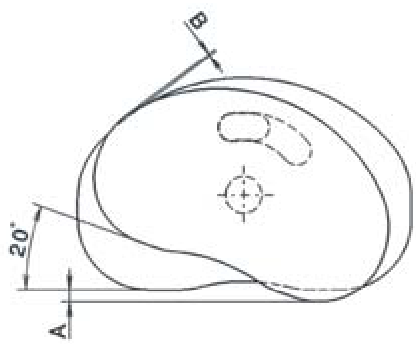

Figure 5.4 The rotational freedom and the tibial overhang (A) of the UCR design.

5.5 MOTION CAPTURE

In this study, an optical infra-red based system produced by Vicon (Vicon motion systems, Oxford, UK) was used, consisting of six T-160 and six T-40S Vicon cameras (**Figure 5.5**), and four Kistler piezoelectric based force platforms (**Figure 5.6**). Vicon T-160 cameras have a 16-megapixel resolution at a frame rate of 120 fps allowing the user to capture the smallest and finer details of the motion. The frame rate can be amplified (while lessening resolution) up to 2000fps to capture fast moving objects. T-40S cameras have a 4-megapixel resolution recording at 515 fps allowing the recording of faster movements. Additionally, both cameras facilitate a "Full Marker Grayscale" feature, which permits the system to compute the radius and centre of each marker more accurately using each pixel of the grayscale information, thus improving system accuracy and precision. Camera recordings for this study were captured at a frequency of 100 fps. Marker trajectories were filtered using a 4th order Butterworth filter with a cut-off frequency of 6 Hz. Marker labelling was done manually. Gaps smaller than 7 frames were filled manually with spline fills; larger gaps were manually filled with pattern fills, or rigid body fills (for pelvis markers only). Force platforms' sampling frequency was set to 1000 fps.

Figure 5.5 The Vicon Optoelectronic Motion Capture T-Series Cameras used in the Gait laboratory.

Reflective 14mm markers with soft and hard bases were fixed on participants' palpable anatomical locations based on the Full-Body Plug-in-Gait (PiG) biomechanical model (**Chapter 2.6.1 Plug-in gait biomechanical model**).

Figure 5.6 Motion capture laboratory, Strathclyde University, Department of Biomedical Engineering.

5.6 THE SIT-TO-WALK TRIALS

This section will present the protocol and laboratory set up for the recording of the STW trials. For the purposes of the study, a height adjustable, armless, backless chair was made; the chair was designed so as to keep the force plates free from any other contact apart from the feet of the sitting subject (**Figure 5.7**). Sit-to-Walk (STW) trials were designed to be more compatible with everyday life activities. Chair height was adjusted to match the participant's knee height. Similarly to Dolecka et al. (2015) and Farquhar et al. (2009), a table with an everyday object was placed three meters in front of the chair.

5.6.1 Participants

Ten controls and twelve OA patients were considered for the STW analysis. Participant recruitment was made in accordance to the inclusion and exclusion criteria presented in **Chapter 5.1 Study design** and the ethics considerations in **Chapter 5.2 Ethics**. All participants gave written informed consent for the study (**APPENDIX V – Participant consent form**). Participant characteristics can be found in **Table 5.2**.

Table 5.2. Participant characteristics.

Characteristic	Control Group (n=10)	OA Group (n=12)
Gender (n), female/male	4/6	6/6
BMI (kg/m^2), mean ±SD	23.56 ±3.04	32.54 ±3.96
Age ($years$), mean ±SD	46 ±7.4	70 ±5.3
Chair height (cm), mean ±SD	50.40 ±2.93	49.85 ±4.25

5.6.2 Data collection

Only a subset of seven markers was used for the analysis of movement strategies in the STW task: the suprasternal notch (CLAV, **Table 2.1**), the metacarpals (LWRA & RWRA), the lateral malleoli (LANK & RANK) and the lateral epicondyles of the femurs (LKNE & RKNE), denoting the position of the torso, hands, feet and knees respectively. The full-body Plug-In Gait model was needed to facilitate the analysis of a series of different tasks, including the STW, which the participants of this study performed during the same motion capture session. Additionally, the processed full-body model aided the validation of the classification results, by allowing the visual inspection of the trials in the Vicon Nexus 3D perspective workspace.

5.6.3 The sit-to-walk movement task

Each participant was asked to comfortably sit on the chair, with each foot placed on a separate force platform (**Figure 5.7**). The subject was then instructed, on the count to three, to rise and walk towards the table to grab an every-day object. Participants were allowed to use arms in order to assist their movements. If a person was unable to stand from that seat height (100%), the chair was adjusted to 115% of his/her knee height. If he/she failed at 115%, the STW trials were terminated. Apart from a single OA participant whose chair was re-adjusted, all other participants performed the task with the chair at 100% of knee height. Subsequently, the participant was instructed to return to the sitting position.

Participants were asked to perform the task in a natural manner similar to standing up from a chair at home to pick up a glass of water from the table in front of them. No other instructions were given. Recordings of the STW movements were repeated until at least three good set of trials were captured.

Figure 5.7 The STW starting position.

5.6.4 Strategy identification

For each recorded trial, two frames, $f1$ and $f2$, were chosen to characterise the initiation and endpoint of the movement strategy. Frame $f1$ depicted the participant preceding the STW movement, whilst frame $f2$ was chosen to reveal the strategy that the participant used between $f1$ and $f2$. Frame $f2$ exists before gait initiation, discounting changes due to side dominance, i.e. left or right leg first to walk. Whole-body centre of mass trajectory and vertical velocity along with the mediolateral ground reaction force may be used to identify the phases of the continuous STW movement (Kerr et al., 2004) and select the desirable frame(s) $f1$ and $f2$. In this study, the drop in the vertical centre of mass trajectory at the beginning of the movement was used to determine, through an automated process, the aforementioned frames $f1$ and $f2$ (**Figure 5.8**). Marker trajectories were filtered using a 4th order Butterworth filter with a cut-off frequency of 6 Hz.

Global coordinates of the seven markers were determined at $f1$ and $f2$ for all trials. The following variables were calculated between $f1$ and $f2$: the angle of the trajectory of the torso marker projected in the sagittal plane with respect to the horizontal ($\mathrm{d}_{\mathrm{ij}}^{\mathrm{torso}}$); the horizontal distance moved by each foot marker in the sagittal plane normalised by body height ($\mathrm{d}_{\mathrm{ijk}}^{\mathrm{foot}}$); the horizontal distance moved by each hand marker in the sagittal plane normalised by body height ($\mathrm{d}_{\mathrm{ijk}}^{\mathrm{hand}}$); the relative x, y and z position of each hand with respect to the lateral epicondyle of the ipsilateral knee normalised by body height ($\left(\mathrm{p}_{\mathrm{ijk}}^{\mathrm{hand}}\right)_{\mathrm{x,y,z}}$). Normalising functions under the assumption that segment lengths are analogous to total body height (Drillis and Contini, 1964). Variables $i, j, and\ k$ designate the participant's identifier, trial number, and sidedness of the operated knee joint, respectively.

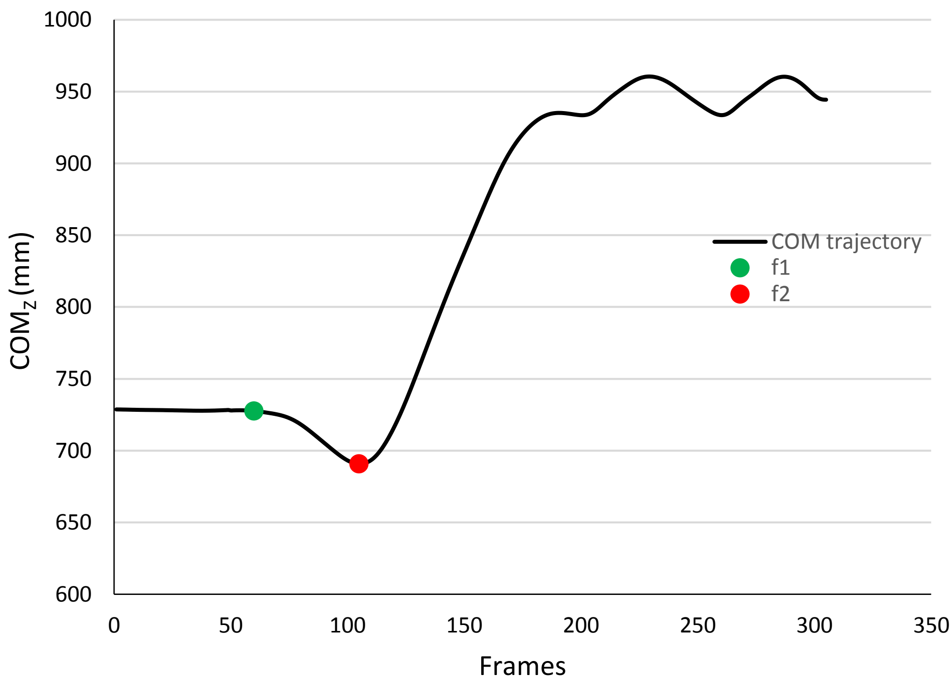

Figure 5.8 Identification of frames $f1$ and $f2$ by the drop of COM curve.

The variables were organised into four separate matrices corresponding to the torso angle (**Equation 5.A**), foot movement (**Equation 5.B**), hand movement (**Equation 5.C**), and the relative position of hands with respect to the knee (**Equation 5.D**). The first row of each matrix contained a concatenation of the participant identifier (A-J: control group, K-V: OA group), trial number $(1-5)$ and, except for the torso matrix, sidedness $(L\ or\ R)$. These algebraic and matrix operations are presenting in **APPENDIX VI – Matlab script**.

Equation 5.A .

$$M_{ij}^{torso\ angle}=\begin{bmatrix} A1 & A2 & & ij & & V5 \\ d_{A1}^{torso} & d_{A2}^{torso} & \cdots & d_{ij}^{torso} & \cdots & d_{V5}^{torso} \end{bmatrix}_{2\times 61}$$

Equation 5.B

$$M_{ijk}^{foot\ mov.}=\begin{bmatrix} A1R & A1L & & ijk & & V5L \\ d_{A1R}^{foot} & d_{A1L}^{foot} & \cdots & d_{ijk}^{foot} & \cdots & d_{V5L}^{foot} \end{bmatrix}_{2\times 122}$$

Equation 5.C

$$M_{ijk}^{hand\ mov.}=\begin{bmatrix} A1R & A1L & & ijk & & V5L \\ d_{A1R}^{hand} & d_{A1L}^{hand} & \cdots & d_{ijk}^{hand} & \cdots & d_{V5L}^{hand} \end{bmatrix}_{2\times 122}$$

Equation 5.D

$$M_{ijk}^{hand\ pos.}$$

$$=\begin{bmatrix} A1R & A1L & \cdots & ijk & \cdots & V5L \\ \left(p_{A1R}^{hand}\right)_x & \left(p_{A1L}^{hand}\right)_x & \cdots & \left(p_{ijk}^{hand}\right)_x & \cdots & \left(p_{V5L}^{hand}\right)_x \\ \left(p_{A1R}^{hand}\right)_y & \left(p_{A1L}^{hand}\right)_y & \cdots & \left(p_{ijk}^{hand}\right)_y & \cdots & \left(p_{V5L}^{hand}\right)_y \\ \left(p_{A1R}^{hand}\right)_z & \left(p_{A1L}^{hand}\right)_z & \cdots & \left(p_{ijk}^{hand}\right)_z & \cdots & \left(p_{V5L}^{hand}\right)_z \end{bmatrix}_{4\times 122}$$

Matrices were submitted to HC (IBM SPSS) separately. Ward's method and Euclidian distance were chosen as the agglomerative algorithm and distance measure respectively. More details regarding the specifics of the clustering prosses are analysed in the preceding chapter **4.2 Hierarchical clustering**. The combination of strategies each participant used to complete the STW movement derives from summation of the strategies identified from each distinct HC. Fisher Exact tests were used to compare OA and control groups for each strategy and to assess the level of movement symmetry in each group. Significance was set at $p = .05$.

5.7 THE CAR INGRESS TRIALS

This chapter describes the recording and analysis of the car ingress task. A mock up car based on a Ford Focus '98, one of the most common cars in the UK, was designed (**Figure 5.9** to **Figure 5.11**) and fabricated (**Figure 5.12** and **Figure 5.13**). A driver's seat, steering wheel, pedals and a roof handle (Ford Focus, 1998) were also fitted on the car. The dimensions of the assembly are shown in **Figure 5.14**. Additional drawings and photographs of the mock up car are presented in **APPENDIX II – Mock up car drawings**.

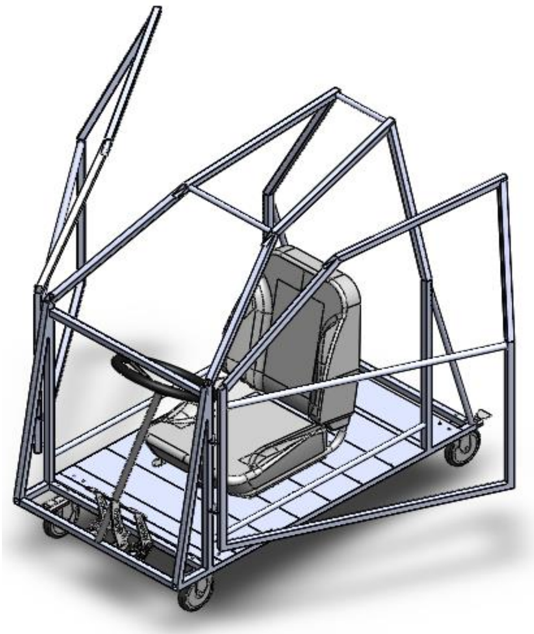

Figure 5.9 Assembly drawing of the mock-up car.

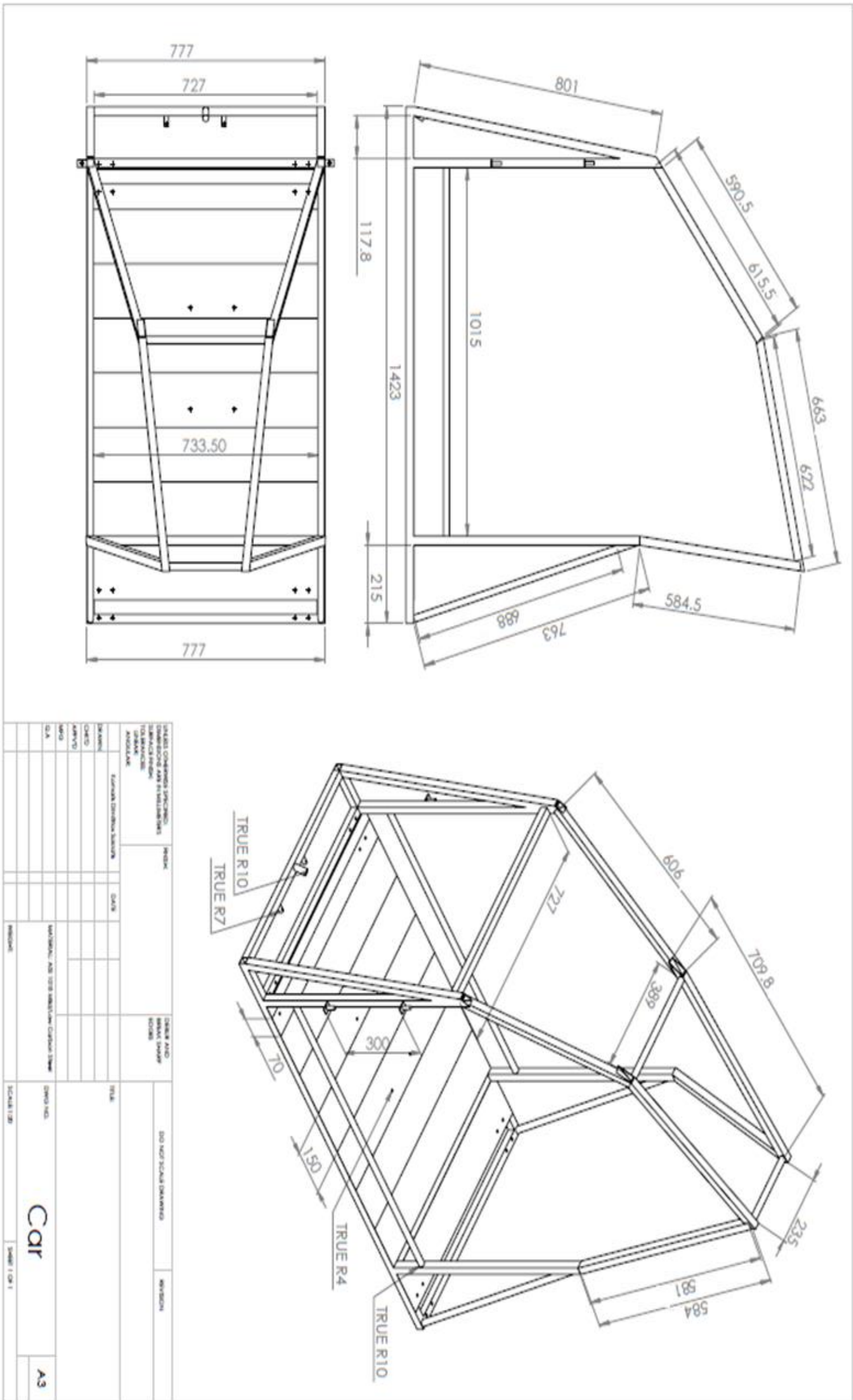

Figure 5.10 Mock up car drawings: the cabin.

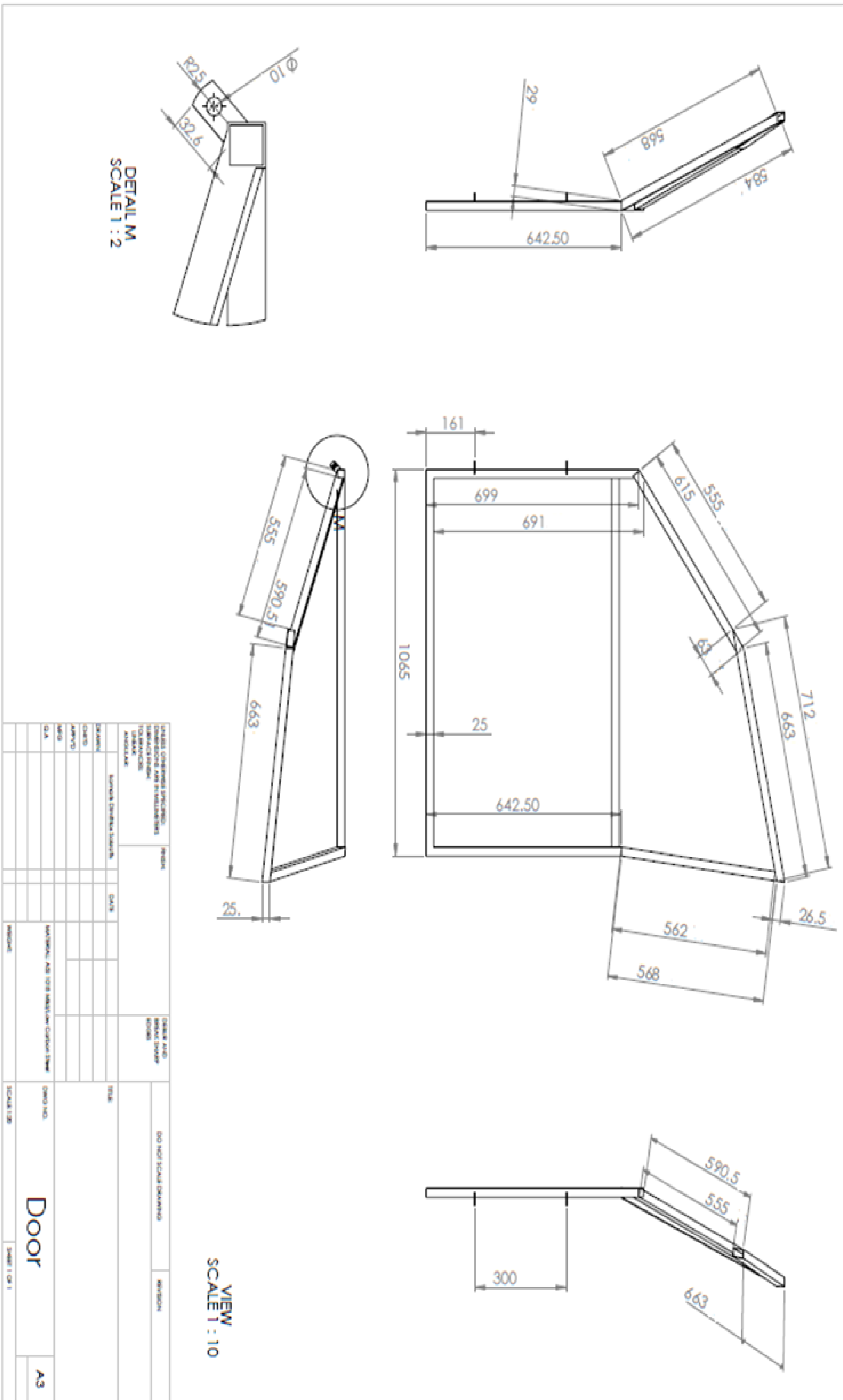

Figure 5.11 Mock up car drawings: the doors.

Figure 5.12 The mock up car.

Figure 5.13. The mock up car (front view).

5.7.1 Participants

Ten control and ten patient participants were considered for this analysis. Patient and control participants were requested to attend a single and three motion capture session(s) respectively; patient participants' sessions took place within four weeks prior to the operation, six to ten weeks after the operation, and around one year after the operation.

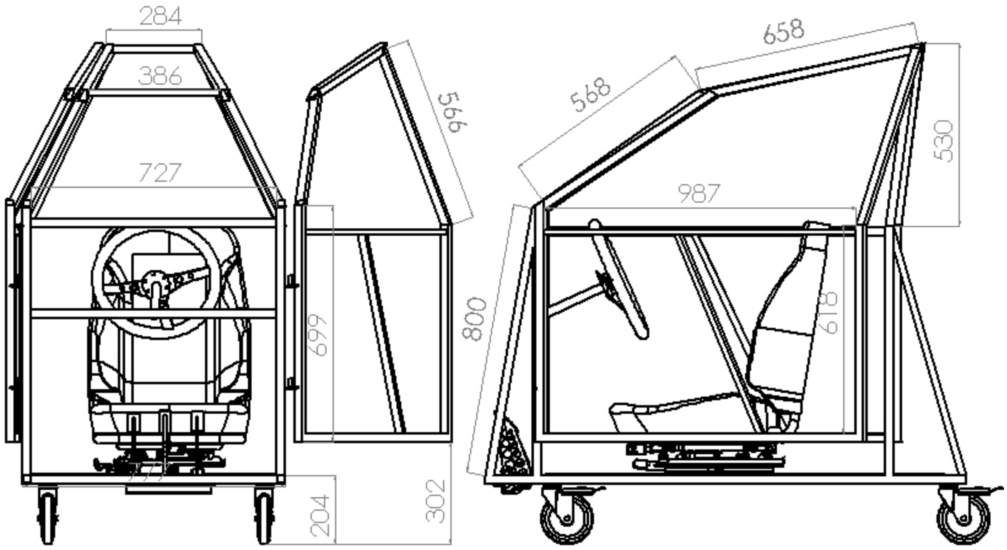

Figure 5.14. Assembly dimensions in mm.

Age, gender, height, weight and affected knee (for patient participants only) were recorded, while body mass index (BMI) was calculated for patient and control participants alike (**Table 5.3**).

Table 5.3. Anthropometric measures.

Characteristic	Control Group (n=10)[1]	Patient Group, Pre-op session[1] (n=10)
Age ($years$), mean ±SD	67.5 ± 7.7	67.9 ± 4.8
Gender (n), female/male	5/5	5/5
Height (mm), mean ±SD	1691.5 ± 122.5	1712.5 ± 88.3
Weight (kg), mean ±SD	71.3 ± 17.5	87.6 ± 11.1
Affected knee, left/right	Not applicable	4/6
BMI (kg/m^2), mean ±SD	24.7 ± 3.6	29.9 ± 3.9

[1] Not the same group of participants as with the STW study.

5.7.2 Data collection

A seven-marker subset of the full body model was used for the car ingress strategies identification: the 7th cervical vertebra (C7, **Table 2.1**), suprasternal notch (CLAV), xiphoid process of the sternum (STRN), fifth metacarpals (LWRA & RWRA), and the lateral malleoli (LANK & RANK). The reconstructed full body model was used for the visual validation of the results that derived from the classification process.

Figure 5.15 The end of the ingress movement.

5.7.3 The car ingress movement task

Participants were instructed to adjust the seat to their preferable driving position prior to testing. The driver's door was also adjusted and locked at one of three positions: door fully open at 60°, door partially open at 50°, or at 35°. The door locking mechanism in presented in the appendix- **Figure A.0.3**. Participants were then instructed to enter the car, sit comfortably, and place their hands on the steering wheel and feet on the pedals (**Figure 5.15**). No other instructions were given. Participants selected their starting position and performed the movement in their own preferred manner. Each participant performed at least three, and up to five repetitions of the ingress movement. The first three successful repetitions with minimum marker loss were used for the analysis.

5.7.4 Strategy identification

One hundred and twenty trials were further processed in Vicon Nexus. Gaps were filled manually with spline fills for gaps with a maximum length of 7 frames, and with pattern or rigid body fills for larger gaps. Marker trajectories were filtered using a 4th order Butterworth filter with a cut-off frequency of 6 Hz. The whole-body centre of mass trajectory was calculated as part of the processed Plug-in gait model and used to manually isolate two frames, $f1$ and $f2$, from each trial. Frame $f1$ was defined as the initiation of the descending ingress movement as identified by the local maximum of the COM trajectory in the sagittal plane (**Figure 5.16**, Left). Frame $f2$ defined the end of the ingress movement at the local minimum of the abovementioned curve, occurring approximately upon the initial contact of the participant's buttocks on the driver's seat (**Figure 5.16**, Right).

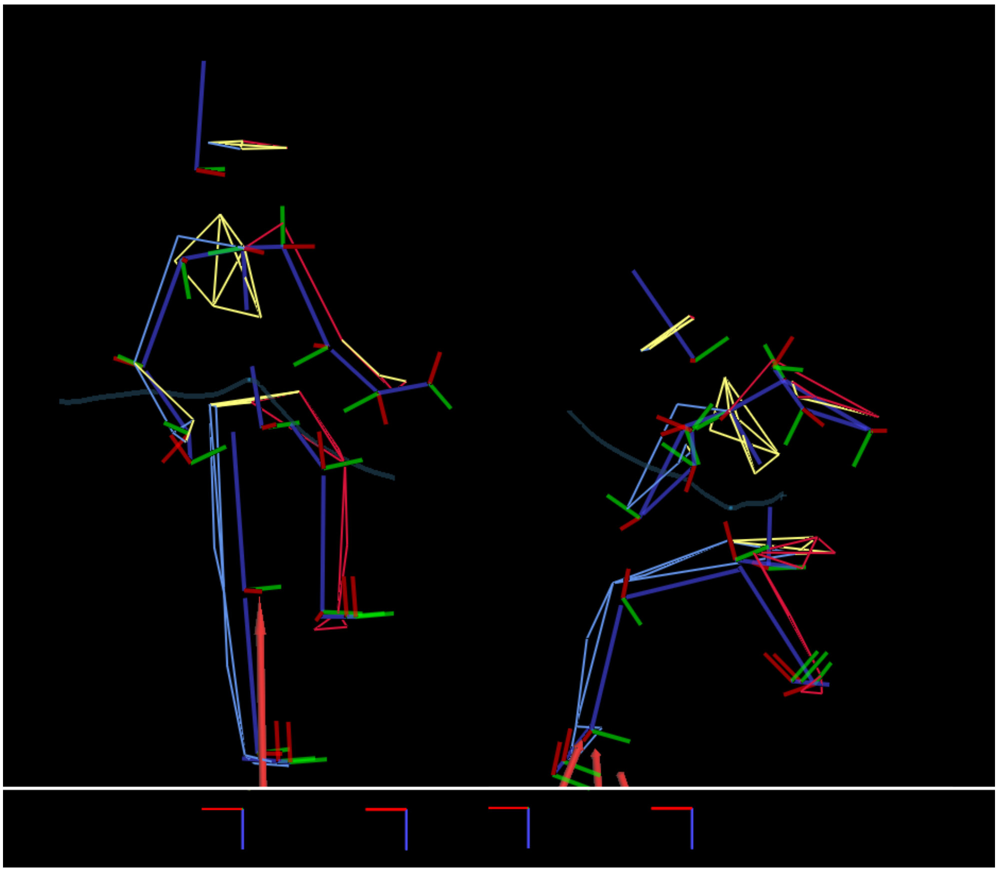

Figure 5.16 Frame $f1$ and $f2$ identification for the car ingress task.

Global coordinates of the seven-marker subset were exported in ASCII files and used to calculate the following variables from frame $f1$ to $f2$: the straight path distance each malleolus marker moved in all global axes normalised by body height ($(d_{ijk}^{foot})_{x,y,z}$); the straight path distance each metacarpal marker moved in all axes normalised by body height ($\left(d_{ijk}^{hand}\right)_{x,y,z}$); the absolute torso rotation angle about the vertical axis as calculated by the trajectories of the 7th cervical vertebra and suprasternal notch (d_{ij}^{torso}). The script for the matrix operations is catalogues in **APPENDIX VI – Matlab script**. Subsequently, the variables were organised into three separate matrices corresponding to the feet, hands, and torso movements as follows: a 7×120 matrix (**Equation 5.E**) containing the progression of the left malleolus marker (rows 2 to 4) followed by the progression of the right (rows 5 to 7); a 4×240 matrix containing the progression of the left and right metacarpals (**Equation 5.F**); a 2×120 matrix containing the torso rotation angles (**Equation 5.G**). The first row of each matrix contained a concatenation of a participant identifier ($A - J$: patient group, $K - T$: control group), trial number ($1 - 3$), a visit indicative (PRE, POST, YEAR, and CTRL) and for the hands matrix, sidedness ($L\ or\ R$). Matrices were submitted to Hierarchical clustering (HC) (IBM SPSS) separately. Ward's method and Euclidian distance were the chosen agglomerative algorithm and distance measure respectively.

Equation 5.E

$$m_{ij}^{foot\ mov.} = \begin{bmatrix} A1_{PRE} & A2_{PRE} & \cdots & ij_{VISIT} & \cdots & T3_{CTRL} \\ (d_{A1L}^{foot})_x & (d_{A1L}^{foot})_x & \cdots & (d_{ijk}^{foot})_x & \cdots & (d_{A1L}^{foot})_x \\ (d_{A1L}^{foot})_y & (d_{A1L}^{foot})_y & \cdots & (d_{ijk}^{foot})_y & \cdots & (d_{A1L}^{foot})_y \\ (d_{A1L}^{foot})_z & (d_{A1L}^{foot})_z & \cdots & (d_{ijk}^{foot})_z & \cdots & (d_{A1L}^{foot})_z \\ (d_{A1R}^{foot})_x & (d_{A1R}^{foot})_x & \cdots & (d_{ijk}^{foot})_x & \cdots & (d_{A1R}^{foot})_x \\ (d_{A1R}^{foot})_y & (d_{A1R}^{foot})_y & \cdots & (d_{ijk}^{foot})_y & \cdots & (d_{A1R}^{foot})_y \\ (d_{A1R}^{foot})_z & (d_{A1R}^{foot})_z & \cdots & (d_{ijk}^{foot})_z & \cdots & (d_{A1R}^{foot})_z \end{bmatrix}_{7X120}$$

Equation 5.F

$$m_{ijk}^{\text{hand mov.}} = \begin{bmatrix} \text{A1R}_{\text{PRE}} & \text{A1L}_{\text{PRE}} & \cdots & \text{ijk}_{\text{VISIT}} & \cdots & \text{T3L}_{\text{CTRL}} \\ \left(d_{\text{A1R}}^{\text{hand}}\right)_x & \left(d_{\text{A1L}}^{\text{hand}}\right)_x & \cdots & \left(d_{\text{ijk}}^{\text{hand}}\right)_x & \cdots & \left(d_{\text{T3L}}^{\text{hand}}\right)_x \\ \left(d_{\text{A1R}}^{\text{hand}}\right)_y & \left(d_{\text{A1L}}^{\text{hand}}\right)_y & \cdots & \left(d_{\text{ijk}}^{\text{hand}}\right)_y & \cdots & \left(d_{\text{T3L}}^{\text{hand}}\right)_y \\ \left(d_{\text{A1R}}^{\text{hand}}\right)_z & \left(d_{\text{A1L}}^{\text{hand}}\right)_z & \cdots & \left(d_{\text{ijk}}^{\text{hand}}\right)_z & \cdots & \left(d_{\text{T3L}}^{\text{hand}}\right)_z \end{bmatrix}_{4\times240}$$

Equation 5.G

$$m_{ij}^{\text{torso angle}} = \begin{bmatrix} \text{A1}_{\text{PRE}} & \text{A2}_{\text{PRE}} & & \text{ij}_{\text{VISIT}} & & \text{T3}_{\text{CTRL}} \\ d_{\text{A1}}^{\text{torso}} & d_{\text{A2}}^{\text{torso}} & \cdots & d_{\text{ij}}^{\text{torso}} & \cdots & d_{\text{V5}}^{\text{torso}} \end{bmatrix}_{2\text{x}120}$$

Feet movement matrix (**Equation 5.E**) was constructed differently than the rest of the matrices in this work: feet and hand movement matrices were drafted with the left and right extremities of the same trial occupying a different column of the matrix (**Equation 5.B**, **Equation 5.C**, **Equation 5.D**, **Equation 5.F**). As a result, those elements of the matrix were clustered as independent data and resulted in the identification of strategies that characterise each limb separately. On the other hand, left and right lower body extremities occupy the same column of the matrix presented in **Equation 5.E**. Thus, the behaviours of both feet for each trial were clustered together, and the identified strategies will describe the behaviour of both limbs collectively. The choice to compose the feet movement matrix differently, is supported by the results of previous studies (Lempereur et al., 2005, Ait El Menceur et al., 2009) that described movement behaviour of the feet jointly (1-foot, 2-foot), and intended to minimise the time for the interpretation of the clustering results.

It should be noted here that no further analysis was conducted to correlate the results of the movement identification process to the knee implant types. This is because by the time this analysis was conducted, only twelve participants have attended all three visits in the motion capture laboratory at the university of Strathclyde. Apart from the small sample size, knee implant randomisation was irregular: out of the 10 participants this study considered, seven received the same type of bearing. Thus, drawing conclusions about the studied sample was impractical.

5.7.5 Time

The time needed to complete the ingress movement, i.e. from frame $f1$ to $f2$, was also measured for each trial. Sets of three trials per participant per visit were averaged to enable comparison among visits, and groups. A repeated mixed measures ANOVA (IBM SPSS) was used to compare the differences in task completion times throughout the patients' rehabilitation process (pre-, weeks post-, and year post-operative) and due to the sidedness of the patients' affected joint (left or right knee). A 2×3 ANOVA was also implemented to identify the interaction between control and year post-operative performance, and participants' height (binned: short, medium, tall) on the task completion time.

5.7.6 Questionnaires

Upon task completion, participants were asked to report on 1) the resemblance of the mock up car to a common car regarding the interior space, legroom, seats and ease of getting in and out, 2) the resemblance of their movements when performing the car task to those when entering a common/their own car, and 3) whether or not they currently drive a car (**APPENDIX IV – Car ingress questionnaire**). Questions 1 and 2 were scaled from one (yes, very accurately) to five (no, not at all).

5.8 CLINICAL OUTCOMES AND QUESTIONNAIRES

The secondary outcomes of the study include the comparison of Oxford knee scores between patient groups (**APPENDIX I – Oxford knee score**) and the assessment of the patient satisfaction through questionnaires (**APPENDIX III – Sit-to-walk questionnaire** and **APPENDIX IV – Car ingress questionnaire**).

5.8.1 Participants

Apart from the movement strategy classification in activities of daily living, this thesis also reports on the questionnaire analysis of patients with end-stage OA who were scheduled to undergo unilateral TKA. Eligible patient volunteers were suitable to receive any of three knee implants:

i. a high congruent mobile,
ii. a high congruent fixed, and
iii. a low congruent fixed bearing (BBraun Columbus® total knee systems).

Recruited patient participants were treated by four different orthopaedic surgeons. An orthopeadic Researcher in Golden Jubilee National Hospital was responsible for the allocation of the implants. Yet, if the randomised allocation was deemed unsuited to the patient's needs, the surgeon would select a more suitable implant for the surgical procedure; this implant could either be one of the remaining two BBraun knees, or any other implant appropriate for the procedure.

Outcome assessors were double blinded to the knee implant allocation of this ongoing study. As a result, this analysis will refer to the study groups as Groups 1-4: groups 1 to 3 arbitrarily correspond to the BBraun knees, whereas group 4 includes patients that received a different design. Out of 26 patient participants, four were initially randomised to another group but either received an alternative BBraun knee system (two patients, one at group 1 and one at group 2) or a completely different implant (Group 4). Patient distribution to the four groups in question, as well as age, are reported in **Table 5.4**.

Table 5.4 Group allocation.

	BBraun Columbus® total knee systems				
Characteristic	Group 1	Group 2	Group 3	Group 4	Total
Number	12	6	6	2	26
Age (*years*), mean ±SD	68±4.3	69±7.5	70.5±4.9	65.5±7.5	68.6±5.7

5.8.2 Questionnaires

Patients were requested to complete an Oxford knee score questionnaire prior to the operation, six to ten weeks after the operation, and approximately one year after the operation. Likewise, throughout each motion capture session, participants were asked to report on 1) difficulty, 2) pain, and 3) tiredness levels following each activity. These questions were scaled from one to five (**Table 5.5**).

Table 5.5 Sit-to-walk and Car Ingress questionnaire.

1) Did you have any difficulty during the task?				
No difficulty at all	Very little difficulty	Moderate difficulty	Extreme difficulty	Impossible to do

2) How would you describe any pain felt during the task?				
None	Very mild	Mild	Moderate	Severe

3) Was the task tiring for you?				
Not tiring at all	Slightly tiring	Moderately tiring	Extremely tiring	Impossible to do

5.8.3 Statistical tests

All questionnaire measures were imported into an Excel spread sheet and further processed with SPSS (IBM). A repeated mixed measures ANOVA was used to compare the differences in OKS throughout the patients' rehabilitation process (pre-, weeks post-, and year post-operative) and due to implant design (groups 1-4). A repeated mixed measures ANOVA joins two unique sorts of one-way ANOVA into a single test: a between-groups, together with a within-subjects ANOVA. Therefore, in the mixed design, one categorical independent variable is a between-subjects variable and the other categorical independent variable is a within-subjects variable. This approach is utilised to test for differences between two or more independent groups while testing subjects at different points of time. The dependent variable (here the results of the OKS) is measured for each group (the knee implant groups) across each time level (the rehabilitations process).

Additionally, a three-way ANOVA was used to determine if there is an interaction effect between strategy preference in the execution of the car ingress task, on the OKS results. Accordingly, the three variables examined were the adopted movement strategies of the feet, hands, and torso, which are described in the upcoming section**: 6.2 The car ingress assessment.** Data from all three patient visits for 10 participants ($n = 30$ visits) were considered (**Table 5.3**).

Friedman tests were used to test for differences in the Sit-to-walk and Car Ingress questionnaire results, throughout the patients' visits in the motion capture laboratory (pre-, weeks post-, and year post-operative). The Friedman test is the non-parametric alternative to the one-way ANOVA with repeated measures. It is used to test for differences of a particular group measured on distinct occasions, when the dependent variable being measured is ordinal (here the difficulty, pain, and tiredness levels as presented in **Table 5.5**).

In order to test the effect of the implant design to the difficulty, tiredness and pain level outcomes, when performing the two activities of daily living one year post-operatively, Kruskal-Wallis H tests were used. The Kruskal-Wallis H test is a non-parametric test that can be used to check if there is a statistically significant difference between groups of an independent variable (groups 1-4) on an ordinal dependent variable (**Table 5.5** questionnaire).

CHAPTER 6. RESULTS

6.1 THE SIT-TO-WALK ASSESSMENT

6.1.1 Strategy identification

Based on the operations described in **Chapter 5.6.4 Strategy identification**, four matrices were submitted to hierarchical clustering, signifying the rotation of the torso (**Equation 5.A**), the progression of the feet (**Equation 5.B**), the progression of the arms (**Equation 5.C**), and the location of the hands relatively to the rest of the body (**Equation 5.D**).

The dendrogram obtained from the HC of the torso matrix suggests the existence of two major clusters, separated by a dashed line (**Figure 6.1).** This is confirmed by the agglomeration schedule coefficient bar chart (**Figure 6.2**): the coefficient of the 60th stage connecting the two major clusters is equal to 200, whereas the same coefficients for the 59th, 58th and 57th stages are 110.5, 82.5 and 62.2 respectively. The increase in the agglomeration coefficient when the two major clusters are combined, cluster 1 and cluster 2, is equal to 89.5, which is much higher than the increase for the previous two stages of 28 and 23.3 respectively. The horizontal axis of the dendrogram also presents the agglomeration coefficient scaled from 1 to 25. Cluster 1 contains 48 subjects and cluster 2 contains 13. Visual inspection of the trials in the Vicon Nexus 3D perspective workspace indicates that the subjects in cluster 1 follow the leaning forward (LF) strategy, which is characterised by a notable flexion of the torso.

The existence of two clusters, each for feet (**Figure 6.3**) and arms (**Figure 6.4),** is further supported by the increase in the agglomeration coefficients in the last stage of each HC (**Figure 6.5** and **Figure 6.6**).

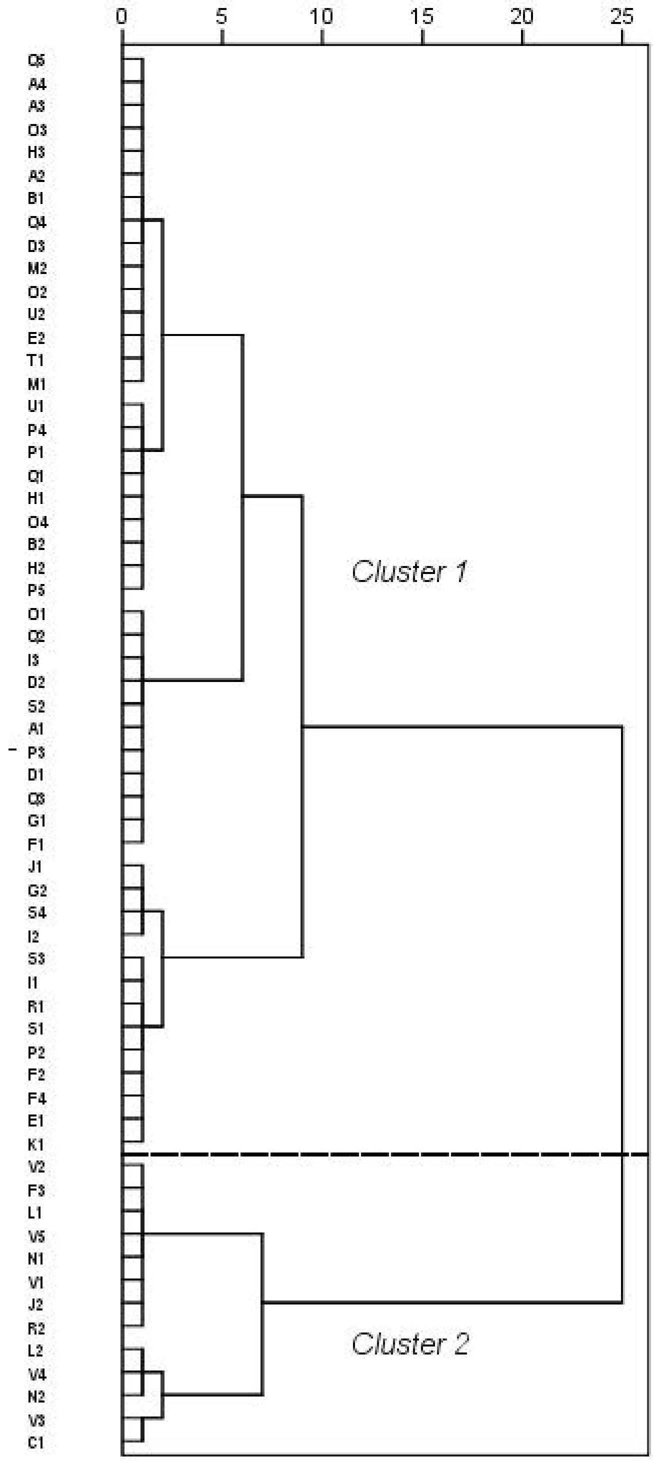

Figure 6.1 Dendrogram of the HC of the torso progression.

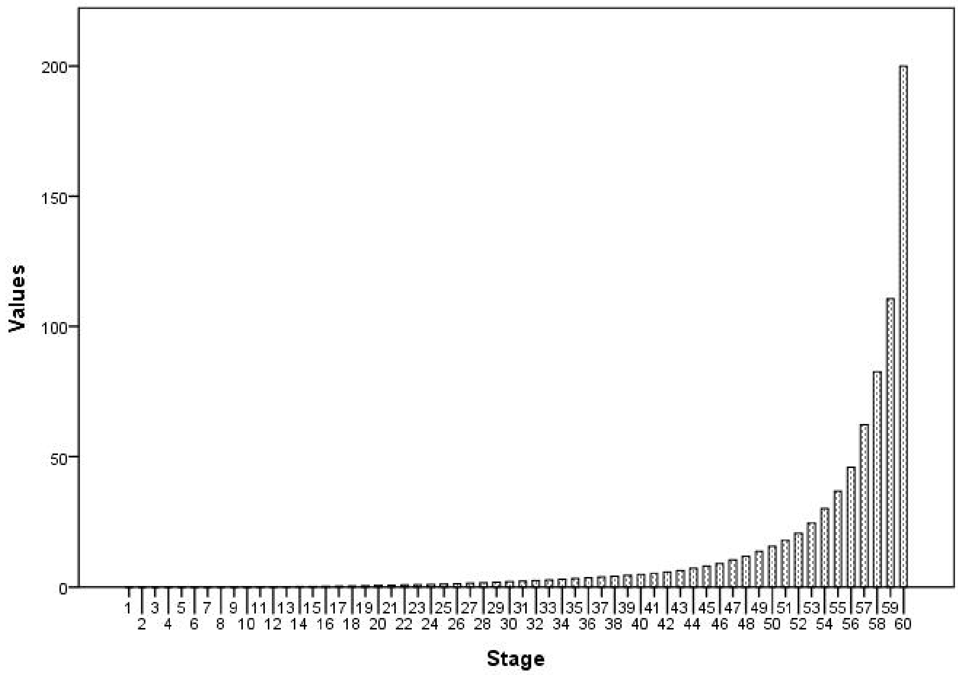

Figure 6.2 Agglomeration schedule coefficient of the torso progression HC.

Cluster 2 from the foot progression clustering (**Figure 6.3**) contains 27 lower extremities and corresponds to the foot backward (FB) strategy. Trials in this cluster show participants dragging their feet posteriorly before rising from the seating position. On the other hand, elements in cluster 1 of the same dendrogram, correspond to rather motionless lower extremities.

Similarly, cluster 2 from the clustering of the arms (**Figure 6.4**) contains 29 upper extremities related to the arm forward (AF) strategy. Participants that adopted this strategy swing their arm(s) forward during the first instances of their recording. As expected, cluster 1 of the hand progression dendrogram includes trials where the participants kept their arms relatively immobile.

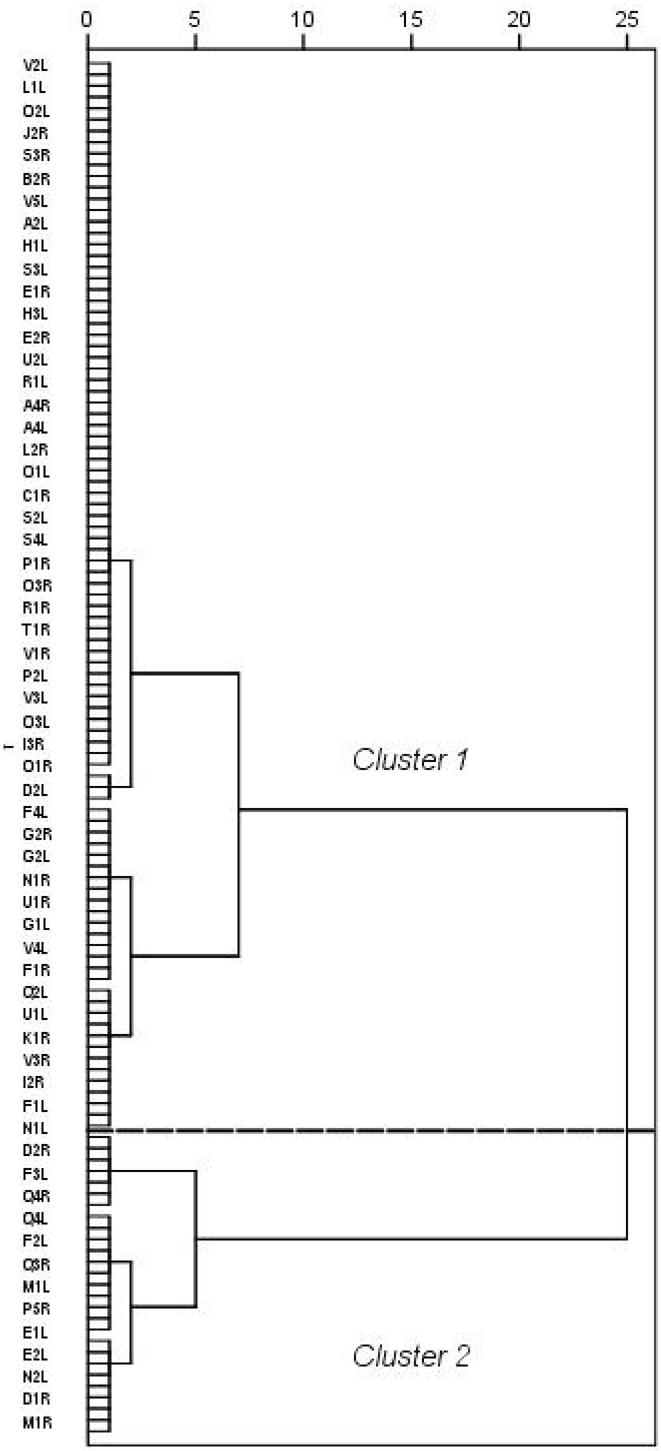

Figure 6.3 Dendrogram of the HC of the foot progression.

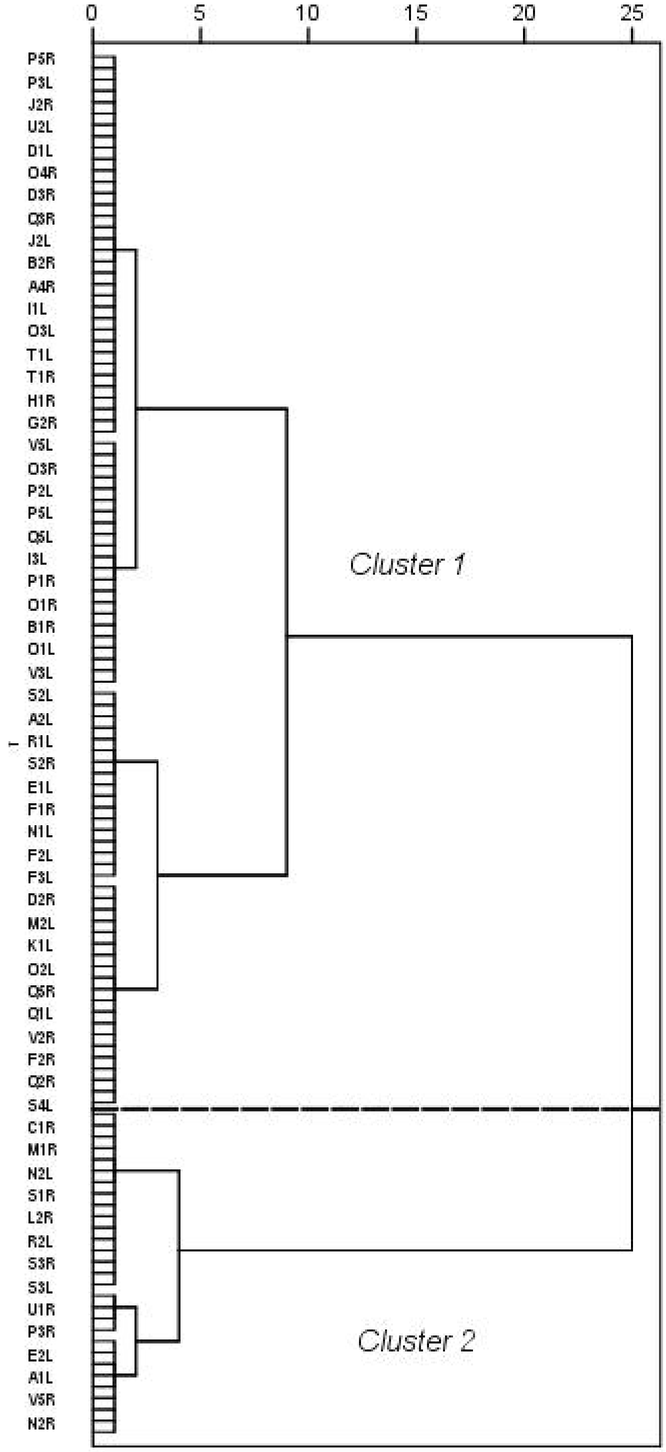

Figure 6.4 Dendrogram of the HC of the arms progression.

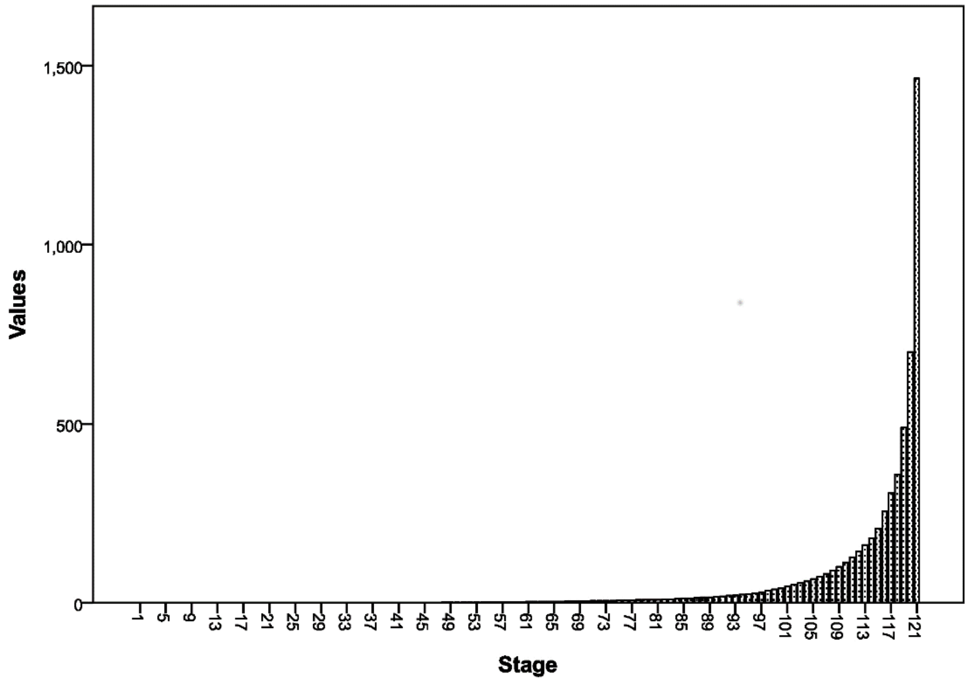

Figure 6.5 Agglomeration schedule coefficient of the feet progression HC.

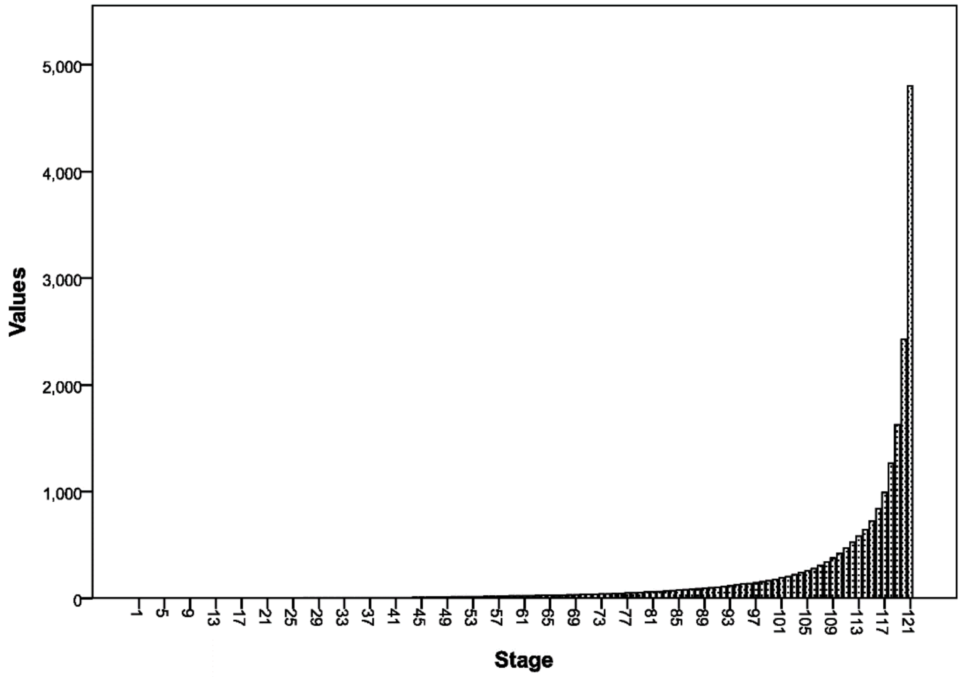

Figure 6.6 Agglomeration schedule coefficient of the arms progression HC.

The classification of the arm strategies is a two-step process: following the 3rd clustering of the progression of the arms (**Equation 5.C**), the 4th clustering of the location of the hands (**Equation 5.D**) considers only immobile upper body extremities (i.e. the extremities belonging in cluster 1 of the dendrogram in **Figure 6.4**). Accordingly, the matrix corresponding to the relative position of the hands (**Equation 5.D**) was diminished from 4×122 to 4×93, by removing the elements of the matrix following the arm forward strategy (i.e. the 29 extremities belonging in cluster 2 of the dendrogram in **Figure 6.4**). The dendrogram (**Figure 6.7**) implies the existence of two to four major clusters. Visual inspection of the trials in Vicon Nexus 3D perspective workspace revealed that extremities belonging in cluster 1, 2 and 3 use three distinct movement strategies.

As a result, HC of the hands position (**Figure 6.7**) and arm progression (**Figure 6.4**) metrices, collectively revealed four different movement strategies: participants that did not use their arms to assist their movement (NA, **Figure 6.7**, Cluster 1), those who pushed the sides of the chair (PC, Cluster 2) or the knees (PK, Cluster 3) to enhance their balance and minimise the loading on the knee joints, and finally, participants that moved their arms forward to increase their momentum and ease the task (AF, **Figure 6.4**, Cluster 2). To visually inspect the results of the hierarchical clustering process, the position of the arms during seat-off is depicted in **Figure 6.8**.

The classification of the arm strategies is a two-step process which aims to increase the descriptiveness of the arms' behaviour: the first clustering of the process (**Figure 6.4**) splits the trials into two groups (immobile and mobile arms), whereas the second step (**Figure 6.7**) was used to further differentiate these findings and reveal additional movement strategies (pushing through the chair, pushing through the knees, and arms forward).

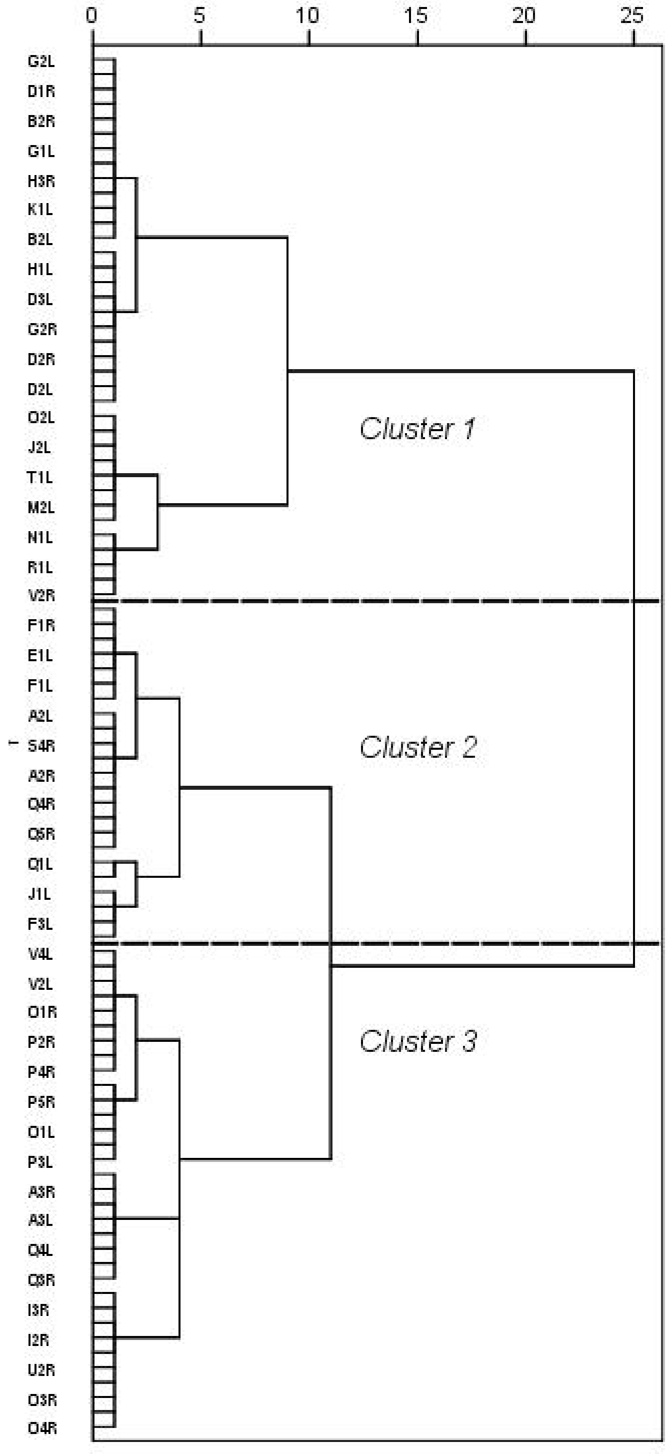

Figure 6.7 Dendrogram of the HC of the spatial position of the hands.

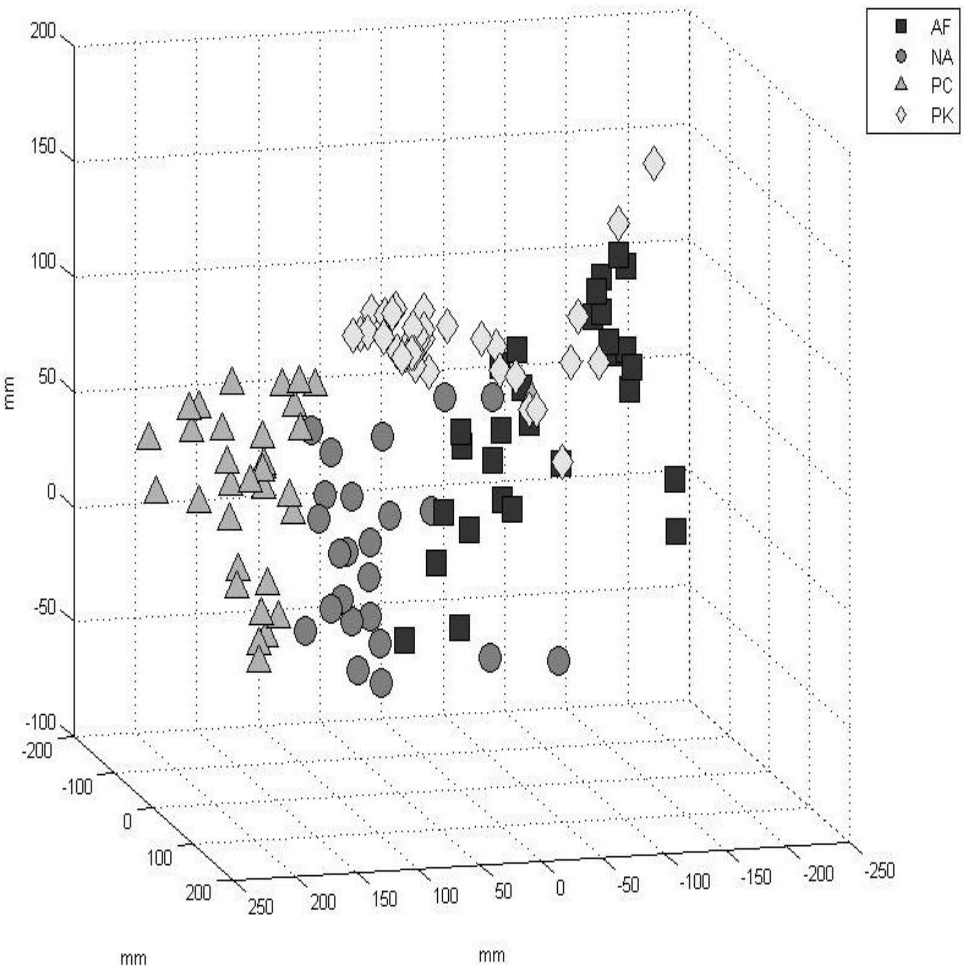

Figure 6.8 Spatial position of the hand extremities with respect to the lateral epicondyle of the ipsilateral knee, adopting the PC, NA, PK and AF strategies at frame f_2.

The strategy each participant used to complete the STW task, derives from the accumulation of the various extremity strategies identified through the clustering process (**Table 6.2**). Bilateral strategies, where the left and right extremities used a matching strategy, are noted with subscript **B**. Asymmetrical strategies are illustrated with subscripts **L** and **R**, for left and right respectively. In the HC of the position of the hands, some irregular movement strategies were classified and clustered among the major clusters of the three-cluster solution. For example, at trials A3, A4 and Q5, participants kept their hand(s) close to the seat at the height of their pelvis until completion of the standing movement. As a result, their trials were clustered as if the participants were pushing through the chair. Similarly, during trials N1 and R1, the hands were floating over the participants' knees but without being in contact, hence, those movements were linked to the push knee strategy. Those irregular movements are in bolt in **Table 6.2.** Even though the process requires the trajectories of seven markers at two frames, entire trials had to be processed to facilitate the validation of the clustering outcome, and estimate the whole-body centre of mass trajectory. As a result, marker obstruction, more often in trials of obese participants, was the primary reason for trial omission (**Table 6.2**).

OA patients adopted the push chair strategy more frequently than the control group ($p = .015$) (In bold, **Table 6.1**). Conversely, control participants potentially tend to favour the push knee strategy, however, the difference between groups was non-significant ($p = .097$). All the other strategies were observed with the same frequency among the two groups in question.

Table 6.1. Strategies: preference among groups.

Type of strategies	Control group (n =26 trials)	OA group (n =35 trials)	$p - value$
Leaning forward, n trials (%)	23 (88.5%)	25 (71.4%)	.128
Foot/feet backward,[a] n trials (%)	9 (34.6%)	11 (31.4%)	.999
Arm(s) forward,[a] n trials (%)	5 (19.2%)	13 (37.1%)	.163
Pushing through the chair,[a] n trials (%)	**4 (15.4%)**	**16 (45.7%)**	**.015**
Pushing through the knee(s),[a] n trials (%)	12 (46.2%)	8 (22.9%)	.097
No arm(s),[a] n trials (%)	6 (23.1%)	6 (17.1%)	.746

In bold: Statistically significant difference between groups.
[a]Each type of strategy refers collectively to all possible bilateral and asymmetrical variations observed.

Table 6.2. Distribution of strategies identified for the recorded trials

Subj.	1st trial	2nd trial	3rd trial	4th trial	5th trial
A	LF+AF_B	LF+NA_B	LF+$\mathbf{PC_B}$	LF+$\mathbf{PC_B}$	
B	LF+PK_B	LF+PK_B			
C	AF_B				
D	LF+FB_R+PK_B	LF+FB_R+PK_B	LF+FB_R+PK_B		
E	LF+FB_L+NA_B	LF+FB_L+AF_B			
F	LF+NA_B	LF+FB_L+NA_B	FB+NA_B	LF+AF_B	
G	LF+PK_B	LF+PK_B			
H	LF+PK_B	LF+PK_B	LF+PK_B		
I	LF+PK_B	LF+AF_L+PC_R	LF+FB_L+PC_B		
J	LF+FB_R+NA_B	PK_B			
K	LF+PK_B				
L	AF_B	AF_B			
M	LF+FB_B+AF_B	LF+FB_B+PK_B			
N	$\mathbf{PK_B}$	FB_B+AF_B			
O	LF+PC_B	LF+PK_B	LF+PK_B	LF+PC_B	
P	LF+FB_L+PC_B	LF+PC_B	LF+FB_B+AF_R+PC_L	LF+FB_L+PC_B	LF+FB_R+PC_B
Q	LF+NA_B	LF+FB_R+NA_B	LF+FB_R+PC_B	LF+FB_B+NA_R+PC_L	LF+FB_B+NA_R+$\mathbf{PC_L}$
R	LF+$\mathbf{PK_B}$	AF_B			
S	LF+AF_R	LF+NA_B	LF+AF_B	LF+NA_B	
T	LF+PK_B				
U	LF+AF_B	LF+PC_B			
V	AF_R+PC_L	PK_R+PC_L	AF_R+PC_L	AF_R+PC_L	AF_R+PC_L

In bold: irregular movement strategies.

Abbreviations used: LF: leaning forward; FB: foot/feet backward; AF: arm(s) forward; NA: no arm(s); PC: arm(s) pushing through the chair; PK: arm(s) pushing through the knee(s); $_{B/R/L/}$: both/right/left.

Apart from the six distinct types of adopted strategies, asymmetrical and bilateral movements were also catalogued (**Table 6.5**). There was no difference between groups in the frequency of use of such feet strategies, ($p = .205$). A small non-significant difference in feet asymmetries among groups, may be attributed in the fact that control participants more frequently drag one of their feet posteriorly, to initiate gait faster. On the other hand, OA patients used considerably more asymmetrical arm strategies ($p = .034$), while the control group adopted nearly entirely, bilateral arm strategies (**Table 6.3**).

Table 6.3. Asymmetries among groups.

Asymmetries	Control group (n =26 trials)	OA group (n =35 trials)	$p - value$
Feet asymmetries, n trials (%)	8 (30.8%)	5 (14.3%)	.205
Hands asymmetries, n trials (%)	**1 (3.8%)**	**9 (25.7%)**	**.034**

In bold: Statistically significant difference between groups.

6.2 THE CAR INGRESS ASSESSMENT

6.2.1 Strategy identification

For the identification of the car ingress strategies, three separate matrices corresponding to the feet (**Equation 5.E**), hands (**Equation 5.F**), and torso movements (**Equation 5.G**) were submitted to HC.

The jump in the rescaled agglomeration schedule coefficient from the two to one cluster solution (**Figure 6.10**), as well as previous numerical and observational studies (Ait El Menceur et al., 2008, Ait El Menceur et al., 2009), suggest a two cluster solution for the HC of the feet progression matrix. The two major clusters are separated by a dash line on the dendrogram generated by the clustering procedure **(Figure 6.9**).

Visual inspection of the trials in Vicon Nexus indicates that trials in cluster 1 and 2 contain participants using the one-foot and two-foot ingress movement strategies respectively. Specifically, participants adopting the one-foot strategy will initiate the ingress movement with their body parallel and laterally to the vehicle’s door, and with the left knee raised and flexed. Then, they will bring their torso inside the mock up vehicle in a continuous movement, while the left foot is landing under the steering wheel and the right is still on the ground working as a pivot foot. An example of this approach is presented in a previous chapter (**Figure 2.23**).

On the other hand, participants using the two-foot strategy will start the movement with their back turned to the vehicle’s door, and then, sit down while still facing outside the vehicle with both feet on the ground. They will then rotate their torso in order to face the anterior of the mock up car, while rising both legs off the ground and bringing them in the interior of the vehicle. This strategy can be seen in **Figure 2.24**.

Similar to the clustering of the feet movement, the HC of the hand movement separated the elements of the matrix into two clusters. Both dendrogram (**Figure 6.11**) and previous studies (Chateauroux and Wang, 2010) also confirm the existence of a two cluster solution. As with the hand and feet clustering of the STW trials (**Figure 6.3** and **Figure 6.4**), the process has distinguished moving from relatively motionless extremities.

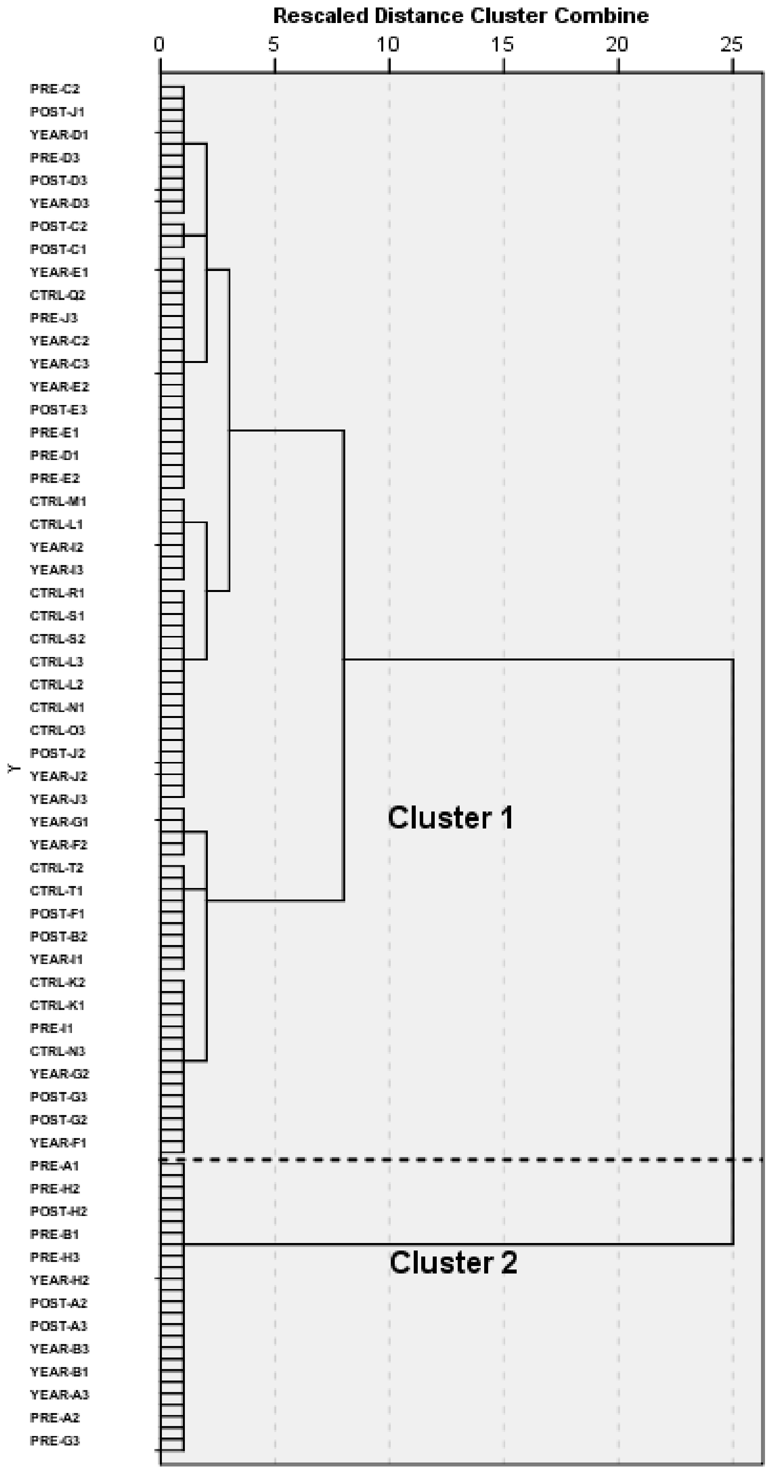

Figure 6.9. Dendrogram of the HC of the feet movement.

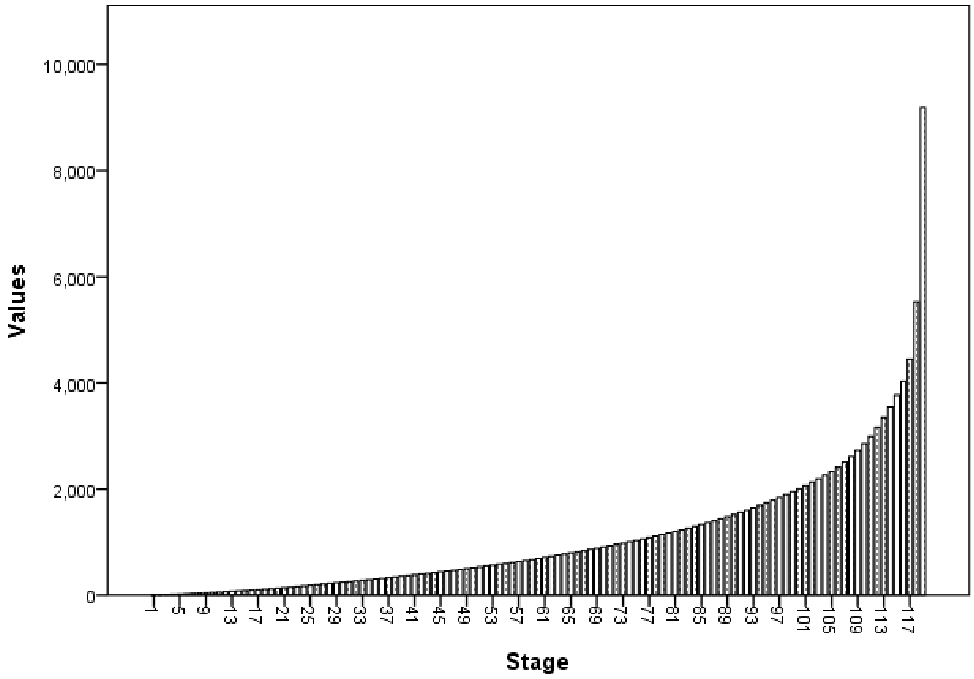

Figure 6.10 Agglomeration schedule coefficient of the feet movement HC.

Extremities belonging in cluster 1 and 2 of the hand movement dendrogram, moved on average 45mm and 231mm in space respectively. Visual inspection of the trials confirmed that the motionless extremities were in fact in contact with an element of the car throughout the biggest part of the ingress movement. The bilateral upper body behaviour of each participant led to the identification of three strategies describing the hands interaction with the vehicle: no-support, single-support, and double-support.

Able-bodied participants adopting the no-support strategy, kept their arms moving freely throughout the ingress movement, and in most of the trials, finished the movement with both hands on the steering wheel. Trials of less able participants clustered in the same category, frequently depict an ongoing attempt to maintain hand support by readjusting their grip on different elements of the environment. Single-support trials portray a pivot hand, typically holding the steering wheel, doorframe, or the seat, whereas the mobile extremity will often swing and grab the wheel by the end of the movement. Finally, double-support trials include participants maintaining support by holding on the steering wheel, door, seat, car frame, or their thighs.

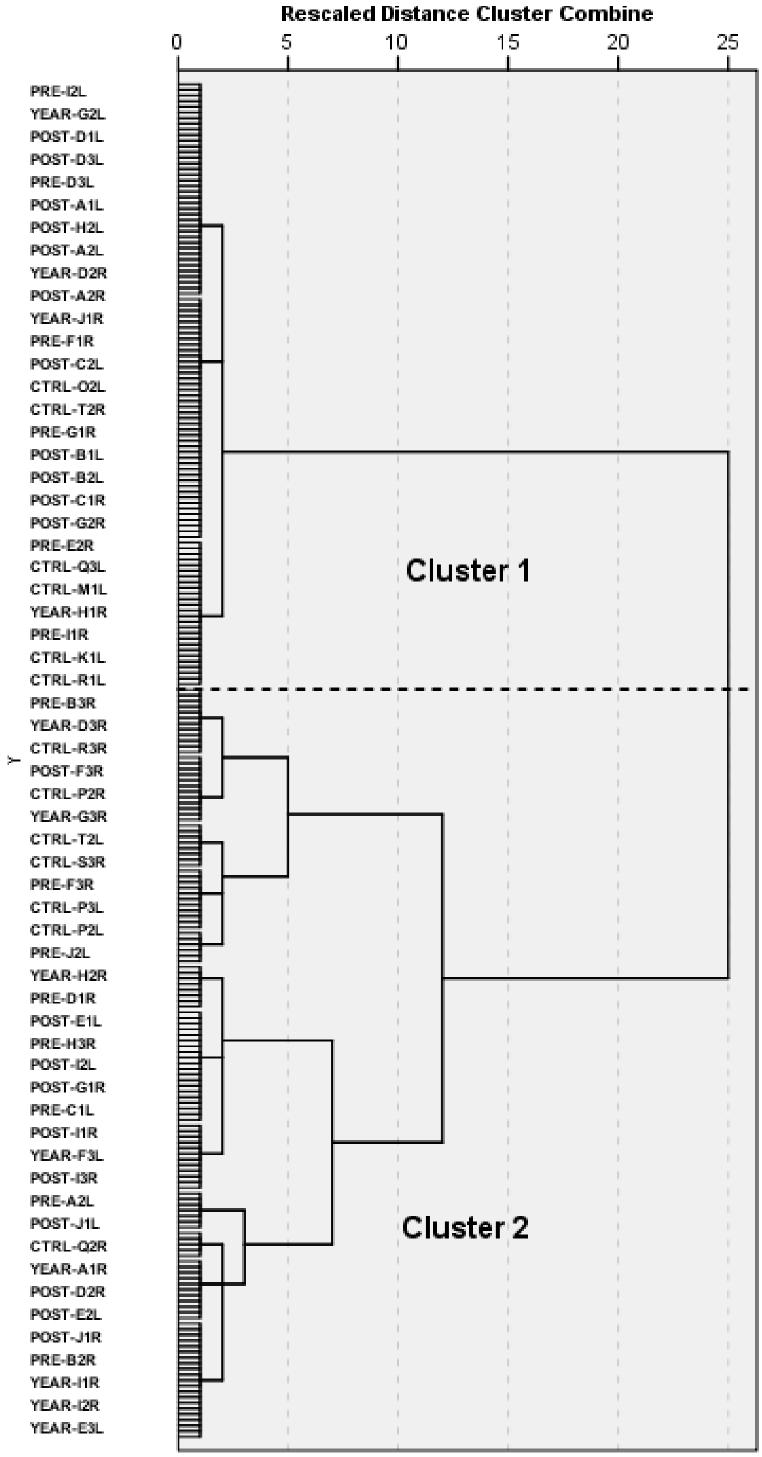

Figure 6.11. Dendrogram of the HC of the hand movement.

The dendrogram obtained from the HC of the torso rotation matrix suggests a range of solutions, extending from two to four major clusters (**Figure 6.13).** The agglomeration schedule coefficient bar chart offers no further insight as well (**Figure 6.12**). Previous research (Lu et al., 2016) proposes allocating the torso movement into two major groups: rotated and straight torso. Trials assigned in the first and second cluster portray participants rotating their torso on an average of 32.8° and 6.8° when entering the vehicle respectively.

Participants with increased torso mobility generally tend to rotate their body to face toward the anterior of the vehicle by the end of their ingress movement (Cluster 1, **Figure 6.13**). On the contrary, participants on the complement cluster (Cluster 2, **Figure 6.13**) will maintain their upper body orientation throughout the task, and in most cases, finish their movement with the steering wheel on their side or even back.

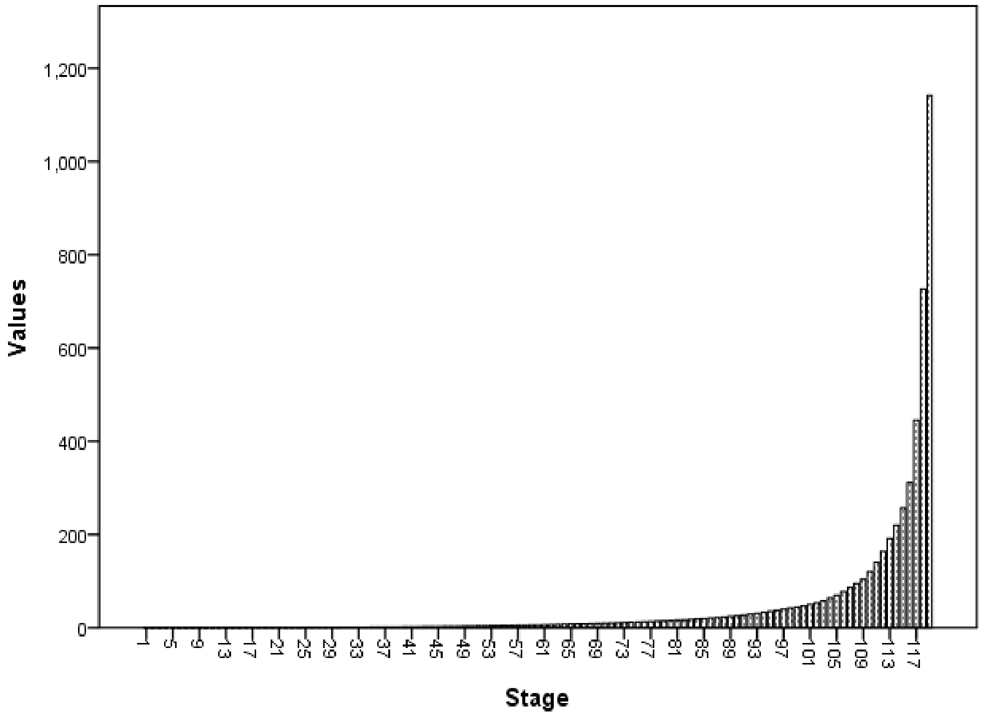

Figure 6.12 Agglomeration schedule coefficient of the torso movement HC.

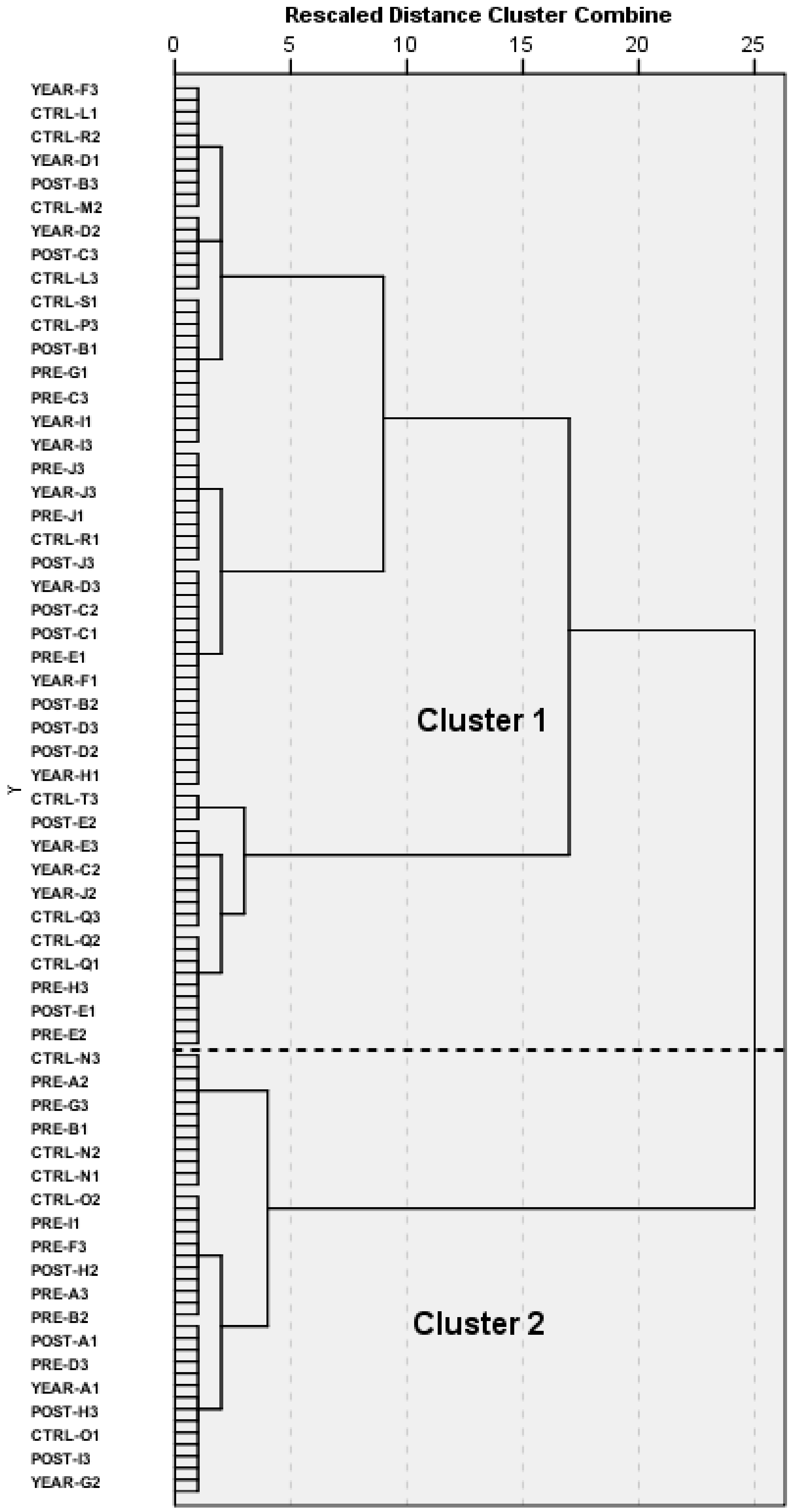

Figure 6.13. Dendrogram of the HC of the torso rotation.

The whole-body strategy each participant used to complete the ingress task, derives from the accumulation of the three segment strategies identified by the clustering process (**Table 6.5**). Twelve whole-body movement strategies emerged from the classification process.

Apart from the unanimous adoption of the one-foot strategy, controls seem to favour the single-support (63%) over the no-support (37%) hand strategy. There were no observed instances of control participants adopting the double support hand strategy. Additionally, the majority of the control group (80%) significantly rotated their torso when entering the vehicle (**Table 6.4**).

Preoperative patients' movement preferences seem to be more scattered across the observed types of strategies. Nevertheless, patient group demonstrated a tendency to switch postoperatively to the same strategies the control participants favour: 57% and 70% follows the single-support hand strategy pre- and year post-operatively respectively; 57% and 67% rotated their torso during the same two testing periods; 63% increased to 73% after a year, for the one-foot strategy.

Table 6.4. Car ingress strategies frequencies.

		Patient Group		
Strategy	Control Group (n=30)	Pre-op (n=30)	Weeks post-op (n=30)	Year post-op (n=30)
Feet				
One-foot, n trials (%)	30 (100%)	19 (63%)	23 (77%)	22 (73%)
Two-foot, n trials (%)	0	11 (37%)	7 (23%)	8 (27%)
Hands				
No-support, n trials (%)	11 (37%)	6 (20%)	10 (33%)	4 (13%)
Single-support, n trials (%)	19 (63%)	17 (57%)	14 (47%)	21 (70%)
Double-support, n trials (%)	0	7 (23%)	6 (20%)	5 (17%)
Torso				
Rotated, n trials (%)	24 (80%)	17 (57%)	21 (70%)	20 (67%)
Straight, n trials (%)	6 (20%)	13 (43%)	9 (30%)	10 (33%)

Table 6.5. Strategies distribution.

	Patient participants			Control Participants	
Trial Code	1st Visit	2nd Visit	3rd Visit	Trial Code	1st Visit
A1	2F-SS-R	2F-SS-S	1F-SS-S	K1	1F-SS-R
A2	2F-SS-S	2F-DS-S	2F-SS-S	K2	1F-SS-R
A3	2F-SS-S	2F-DS-S	2F-SS-S	K3	1F-SS-R
B1	2F-DS-S	1F-SS-R	2F-DS-R	L1	1F-NS-R
B2	2F-NS-S	1F-SS-R	2F-SS-S	L2	1F-NS-R
B3	1F-NS-R	1F-SS-R	2F-SS-S	L3	1F-NS-R
C1	1F-SS-R	1F-DS-R	1F-SS-R	M1	1F-SS-R
C2	1F-SS-R	1F-DS-R	1F-SS-R	M2	1F-SS-R
C3	1F-DS-R	1F-SS-R	1F-DS-R	M3	1F-NS-R
D1	1F-SS-S	1F-SS-R	1F-SS-R	N1	1F-NS-S
D2	1F-SS-S	1F-SS-R	1F-DS-R	N2	1F-NS-S
D3	1F-SS-S	1F-SS-R	1F-SS-R	N3	1F-SS-S
E1	1F-DS-R	1F-NS-R	1F-SS-R	O1	1F-SS-S
E2	1F-SS-R	1F-NS-R	1F-SS-R	O2	1F-SS-S
E3	1F-SS-R	1F-NS-R	1F-NS-R	O3	1F-SS-S
F1	1F-SS-S	1F-NS-R	1F-NS-R	P1	1F-NS-R
F2	1F-SS-S	1F-NS-R	1F-SS-S	P2	1F-NS-R
F3	1F-NS-S	1F-NS-R	1F-NS-R	P3	1F-NS-R
G1	2F-DS-R	2F-SS-S	1F-SS-S	Q1	1F-NS-R
G2	2F-DS-R	1F-DS-S	1F-SS-S	Q2	1F-SS-R
G3	2F-DS-S	1F-DS-R	1F-SS-S	Q3	1F-SS-R
H1	2F-SS-R	2F-SS-R	2F-DS-R	R1	1F-SS-R
H2	2F-SS-R	2F-SS-S	2F-SS-R	R2	1F-SS-R
H3	2F-SS-R	2F-SS-S	2F-SS-S	R3	1F-NS-R
I1	1F-DS-S	1F-SS-S	1F-SS-R	S1	1F-SS-R
I2	1F-SS-S	1F-NS-R	1F-SS-R	S2	1F-SS-R
I3	1F-SS-R	1F-SS-S	1F-DS-R	S3	1F-SS-R
J1	1F-NS-R	1F-NS-R	1F-SS-R	T1	1F-SS-R
J2	1F-NS-R	1F-NS-R	1F-NS-R	T2	1F-SS-R
J3	1F-NS-R	1F-NS-R	1F-SS-R	T3	1F-SS-R

Abbreviations used: foot strategies: one-foot (**1F**) and two-foot (**2F**); hand strategies: no-support (**NS**), single-support (**SS**) and double-support (**DS**); torso strategies: straight (**S**) and rotated (**R**).

6.2.2 Time

A mixed between-within subjects ANOVA was also conducted to compare the effect of the sidedness of the affected joint (left or right knee) throughout the rehabilitation process of the TKA group (pre-, weeks post-, and year post-operative), in the time needed to complete the car ingress task. There was no significant interaction between sidedness and rehabilitation stage ($\text{Wilk's}\,\Lambda = .552, F(2,7) = 2.839,\ p = .13, \text{partial}\,\eta^2 = .45$). Moreover, there was no significant main effect for the rehabilitation stage ($\text{Wilk's}\,\Lambda = .619, F(2,7) = 2.151,\ p = .19,\ \text{partial}\,\eta^2 = .38$), or the sidedness ($F(1,8) = 3.097, p = .12,\ \text{partial}\,\eta^2 = .28$). The non-significant effect of sidedness in the time needed to complete the task, can be seen in the first section of **Table 6.6**.

In addition, a two-way ANOVA examined the effect of height, for the control and (year post-operative) patient groups, in the time outcome measure. There was no significant interaction between the two variables, $F(2,14) = 1.751, \mathrm{p} = .21, \text{partial}\,\eta^2 = .20$. Furthermore, the main effect of group was non-significant ($p = .69$), as was the main effect of height ($p = .89$). All effects are reported as non-significant at $p > .05$. Mean and standard deviation values for task completion time were also calculated for the above-mentioned sub-groups of the sample (**Table 6.6,** 2nd section).

The average times to complete the activity for the four groups in question (control, pre-, post-, and year post-operatively) are also presented in the last row of **Table 6.6**.

6.2.3 Questionnaires

Following each activity, participants completed a short questionnaire regarding 1) the resemblances of the mock up car to a common car, 2) the resemblance of their movements when entering the vehicle to those when entering a common car, and 3) whether they currently drive.

Participants reported that the mock up resembled a common car very accurately (85%), to some extent (12.5%), or somewhat (2.5%). When relating their movements while performing the ingress task to those when accessing a common/their own car, 77.5% described them matching very accurately and 22.5% to some extent. All participants reported as drivers at the time of the experiment.

Table 6.6. Task completion times.

	Control Group (n=30)			Patient Group: Pre-op (n=30)		Patient Group: Weeks post-op (n=30)		Patient Group: Year post-op (n=30)		
Sidedness				**Left**	**Right**	**Left**	**Right**	**Left**		**Right**
Time (sec), mean ± SD				1.54 ± .42	1.59 ± .29	1.94 ± .37	1.42 ± .40	1.45 ± .04		1.20 ± .22
Height	**Tall**	**Med.**	**Short**					**Tall**	**Med.**	**Short**
Time (sec), mean ± SD	1.17 ± .01	1.55 ± .30	1.39 ± .15					1.44 ± .05	1.21 ± .22	1.30 ± .25
Average										
Time (sec), mean ± SD		1.42 ± .23		1.57 ± .36		1.63 ± .46			1.30 ± .21	

6.3 OXFORD KNEE SCORE AND QUESTIONNAIRES

Even by observation, the total mean values of the OKS (**Table 6.7**) reflect a strong numerical change in this outcome measure throughout their therapy: from a score of 38.23 pre-operative, to 28.50 and 20.73 weeks and year post-operatively respectively (**Table 6.7,** in bold). Nevertheless, descriptive statistics are not fit to detect statistical differences among sub-groups, i.e. the four knee implant groups.

Table 6.7 Descriptive statistics: mean and Std. of the OKS outcome measure between the different groups.

	Group	OKS Mean	Std. Deviation	N
Pre-operative	1	36.92	7.657	12
	2	43.50	4.680	6
	3	35.83	4.309	6
	4	37.50	3.536	2
	Total	**38.23**	6.581	26
Weeks Post-operative	1	29.00	7.592	12
	2	29.00	9.818	6
	3	26.00	4.290	6
	4	31.50	7.778	2
	Total	**28.50**	7.290	26
Year Post-operative	1	22.00	5.831	12
	2	19.83	3.869	6
	3	18.17	3.869	6
	4	23.50	3.536	2
	Total	**20.73**	4.960	26

A Levene's test for homogeneity of variances for each combination of the groups was used to test that the error variance of the dependent variable is equal across groups ($p > .05$). There was no significant interaction between knee implant designs and rehabilitation stage (**Figure 6.14**) ($\text{Wilk's}\,\Lambda = .701, F(6{,}42) = 1.361,$ $\text{p} = .25,\ \text{partial}\,\eta^2 = .163$). Even though there was no significant main effect for the implant design ($F(3{,}22) = .744,\ \text{p} = .537, \text{partial}\,\eta^2 = .092$), there was a statistically significant main effect for the rehabilitation stage ($\text{Wilk's}\,\Lambda =$ $.126, F(2{,}21) = 73.155, \text{p} < .005,\ \text{partial}\,\eta^2 = .874$) (**Table 6.7**). Pairwise comparisons of the three timepoints (**Table 6.8**), revealed the change in the OKS outcome measure was statistically significant for each pair of time points ($p < 0.5$), i.e. pre-operatively versus weeks post-operatively, weeks post-operatively versus one year post-operatively, and finally pre-operatively versus one year post-operatively.

Table 6.8 Pairwise Comparisons of time points.

(I) Time	(J) Time	Mean Difference OKS (I-J)	Std. Error	Sig.
Pre	Weeks	9.563	1.733	**.001**
Pre	Year	17.562	1.438	**.001**
Weeks	Year	8.000	1.468	**.001**

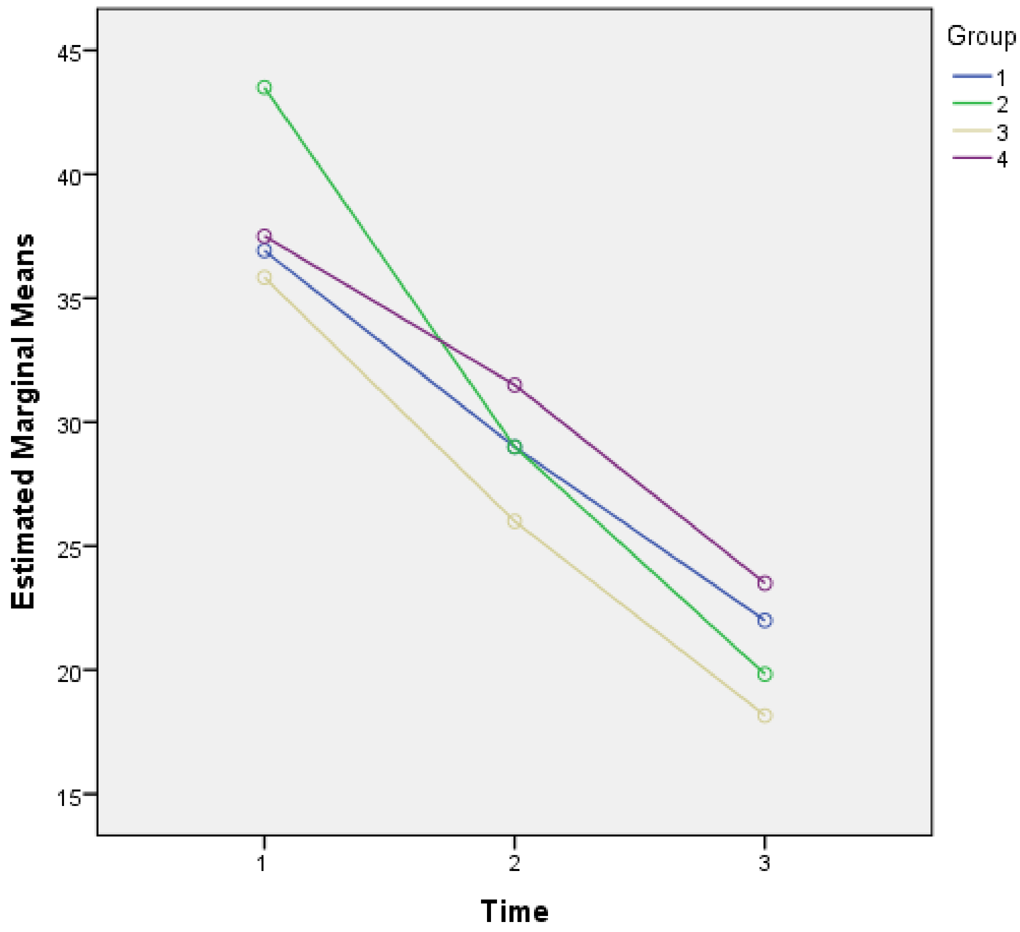

Figure 6.14 Change of the OKS measure (vertical axis) among groups over time (1: pre-op, 2: weeks post-op, 3: year post-op).

The OKS were also compared to the movement patterns participants used to complete the car ingress task. The effect of movement strategy adoption for the feet (two groups: One-foot or Two-foot), hands (three groups: No, Single, or Double support), and torso (two groups: Rotated and Parallel to the vehicle) on the results of the patient reported outcome measures were tested with a three-way ANOVA (**Table 6.9**). There was no statistically significant three-way interaction between feet, hands, and torso strategies, $F(1,79) = .661$. Furthermore, there was no statistical main effect for none of the considered body segment strategies in the OKS outcome measure (**Table 6.9**).

Table 6.9. Interaction between strategy adoption and OKS.

Dependent Variable: OKS			
Source	df	F	Sig.
Feet	1	0.537	0.466
Hands	2	0.531	0.590
Torso	1	0.000	0.992
Feet * Hands * Torso	1	0.194	0.661
Error	79		

Apart from the Oxford knee score assessment, Friedman tests were also used to indicate how the patients reported levels of difficulty, pain, and tiredness differed among three time-points. The bespoke questionnaires are included in the appendices (**APPENDIX III – Sit-to-walk questionnaire** and **APPENDIX IV – Car ingress questionnaire**).

The test statistic indicates that there was a statistically significant difference for the perceived difficulty and pain levels, for both the sit-to-walk and car ingress tasks (in bold, $p - values$, **Table 6.10**). This improvement over time can also be observed in the bar charts bellow: **Figure 6.15** to **Figure 6.18**.

Those tests, demonstrated that there is a difference in the answers given by the patients throughout their motion capture sessions, but do not determine when that difference occurred. To identify this, Wilcoxon signed-rank post hoc tests were used. Wilcoxon tests were run for the different three combinations of the repeated measurements: 1) pre- to weeks post-op, 2) pre- to year post-op, and 3) weeks to year post-op (1-3, **Table 6.10**). The significance level for the Wilcoxon tests was set to .017 after a Bonferroni adjustment.

Table 6.10 Friedman and post hoc tests.

	Sit-to-walk			Car ingress		
	Difficulty	Pain	Tiredness	Difficulty	Pain	Tiredness
$Chi-square, x^2_{(2)}$ [a]	7.82	28.10	4.67	16.44	23.07	3.20
$p-value$ [a]	**.020**	**.001**	.097	**.001**	**.001**	.202
1. Pre- to Weeks post-op[b]	.038	**.001**[c]	-	.062	**.003**[c]	-
2. Pre- to Year post-op[b]	**.017**[c]	**.001**[c]	-	**.001**[c]	**.001**[c]	-
3. Weeks to Year post-op[b]	.564	.157	-	**.010**[c]	**.013**[c]	-

[a]provides the test statistic (χ^2) value, degrees of freedom, and the significance level ($p-value$) for the Friedman test.
[b]provides the significance level ($p-value$) for the Wilcoxon signed-rank tests.
[c]Significance level is equal to .017 after Bonferroni adjustment.
In bold: statistical significant result

Pain seems to elevate immediately after the operation: there was a statistically significant reduction in perceived pain before versus a few weeks after the surgery, for both examined tasks ($p = .001$ and $p = .003$ for the STW and Car ingress respectively). A further reduction in pain levels is observed from weeks to year post-operatively in the car ingress task ($p = .013$). On the other hand, the difficulty level to perform an activity level seems to decrease only after a year have passed since surgery (before versus a year after, $p = .017$ and $p = .001$ for the STW and the Car Ingress test respectively). Interestingly, improvement in pain levels during the STW assessment seem to reach cap only weeks after the operation (pre- versus weeks postoperatively, $p = .001$), since no statistically significant difference is observed from weeks postoperatively to a year after surgery ($p = .157$).

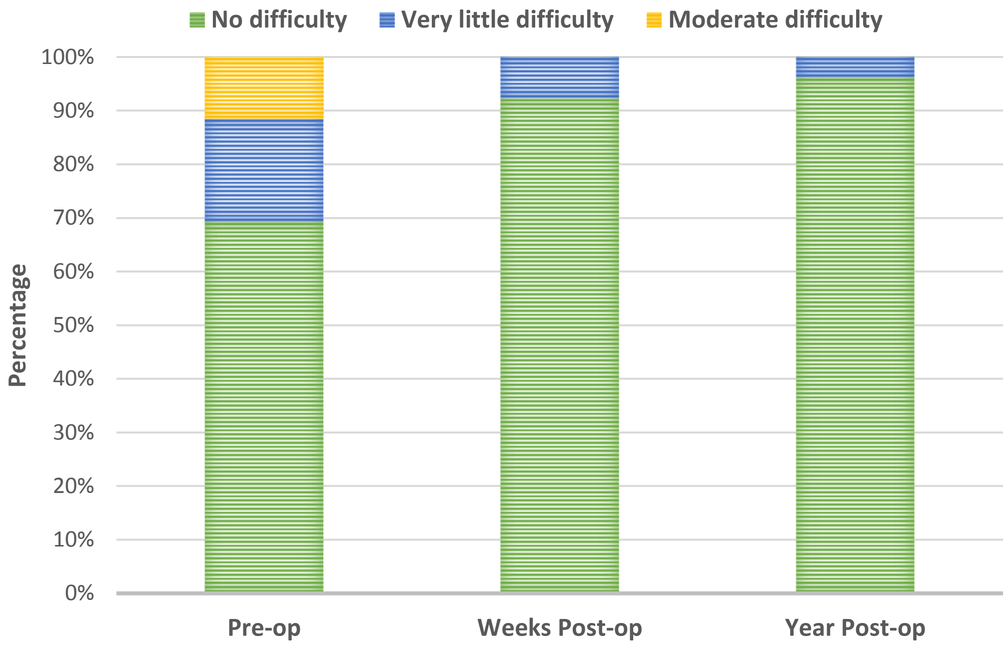

Figure 6.15 Reported difficulty levels for the STW task

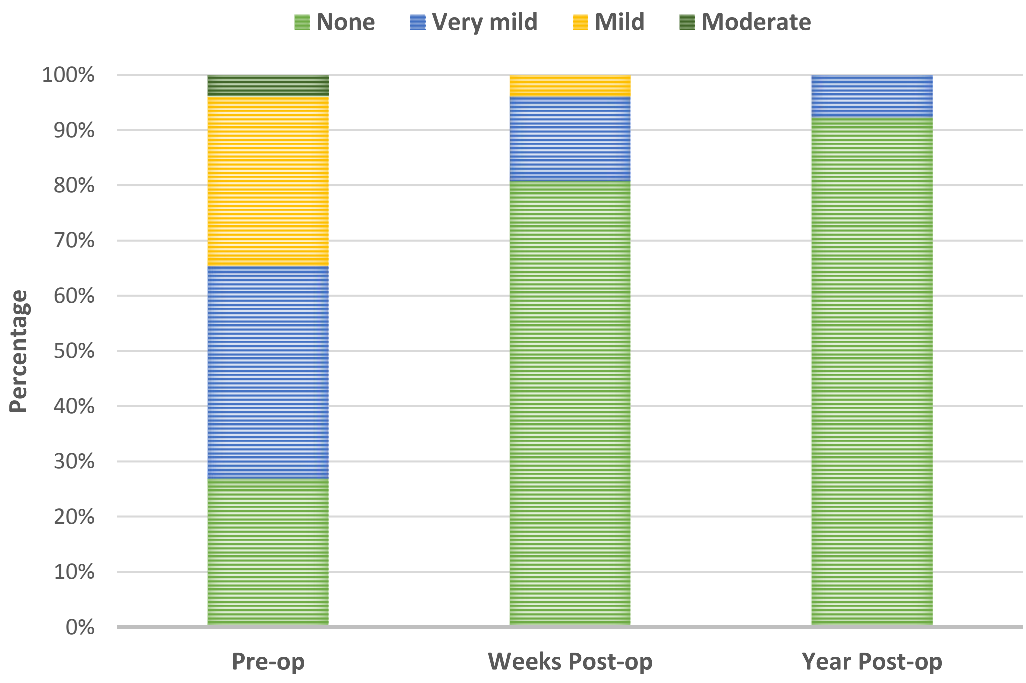

Figure 6.16 Reported pain levels for the STW task**.**

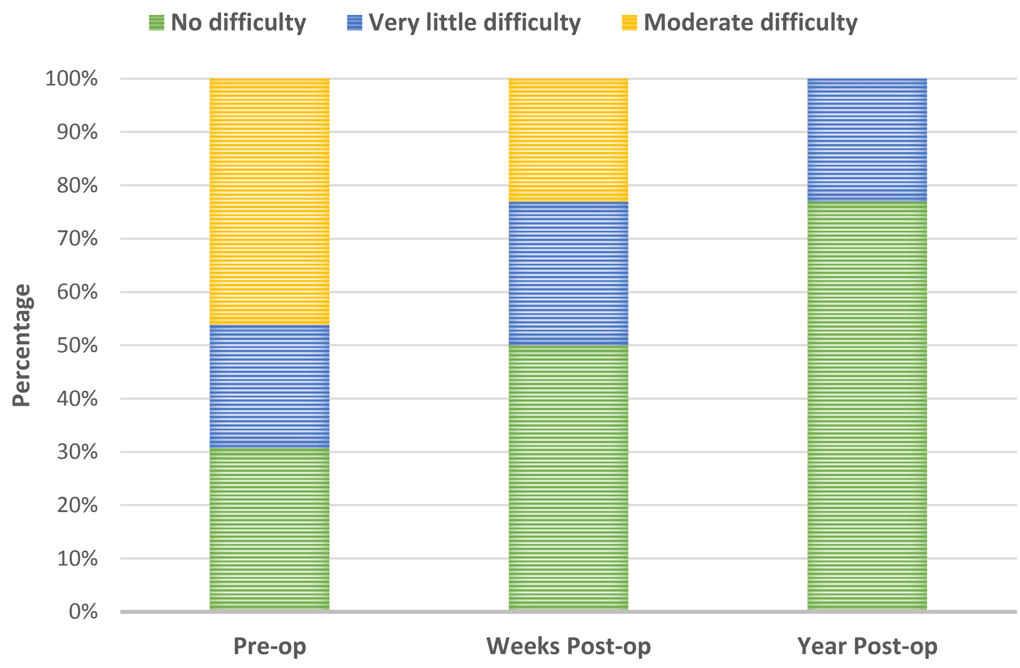

Figure 6.17 Reported difficulty levels for the car ingress task.

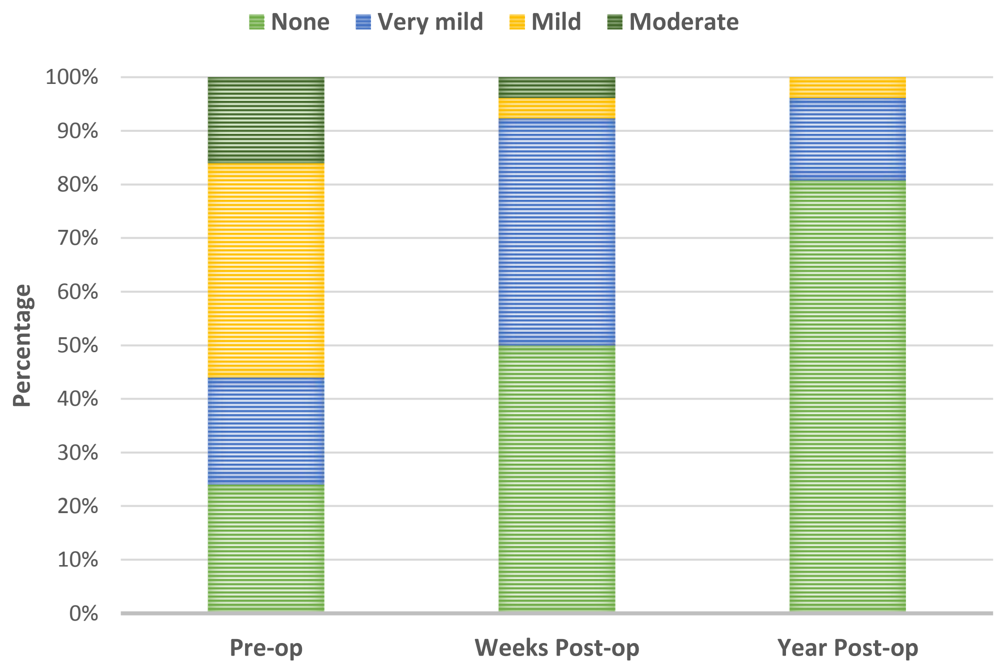

Figure 6.18 Reported pain levels for the car ingress task.

The aforementioned test offered an insight into the improvement of the patients in a years' time. Yet, to ascertain the effect of the implant design to the difficulty, tiredness and pain level outcomes, Kruskal-Wallis H tests were used. The Kruskal-Wallis H test is a rank-based nonparametric test that may be implemented to examine if there are statistically significant differences between two or more groups of an independent variable on an ordinal dependent variable. Here, the test was used to understand whether questionnaire outcomes, measured on a scale from 1-5, differed based on the knee design (four knee implant groups).

The test showed that there wasn't a statistically significant difference in perceived difficulty, pain, and tiredness levels from the preoperative to the one-year postoperative assessment, between all four groups in question ($p - values$, **Table 6.11**). It should be noted, that tiredness levels were reported to be always minimal during both visits. Although changes in the perceived pain were non-significant, the relative low $p - value$ ($.075$, , **Table 6.11**) indicates that knee design may affect the pain outcome measure; if that is case, a bigger sample size may reveal further insights into the effects of knee bearings in such clinical outcomes.

Table 6.11 Kruskal-Wallis H test statistics and p-values.

	Sit-to-walk			Car ingress		
	Difficulty	Pain	Tiredness[c]	Difficulty	Pain	Tiredness
$Chi - square, x^2_{(2)}$[a]	1.167	2.413	-	3.333	6.894	5.275
$p - value$[b]	.761	.488	-	.343	.075	.153

[a]provides the test statistic (χ^2) value, degrees of freedom, and the significance level ($p - value$) for the Friedman test.
[b]provides the significance level ($p - value$) for the Wilcoxon signed-rank tests.
[c]tiredness behaviour was linear, and hence no test statistic was calculated.

CHAPTER 7. DISCUSSION AND CONCLUSION

7.1 THE SIT-TO-WALK ASSESSMENT

7.1.1 Movement strategy preference

A novel numerical procedure using kinematic and kinetic data from motion capture trials and statistical clustering methods, was used to identify and compare movement patterns during the STW movement task. Even though HC was previously used to analyse motion capture data (Ait El Menceur et al., 2009, Park et al., 2005), to date, the identification of movement strategies in the STS and STW movement has been achieved only via observation of video recordings (Dolecka et al., 2015). Additionally, originalities in the execution of the clustering approach are discussed in the forthcoming sections: **7.1.2** and **7.2.4.** The results obtained in this study are in good agreement with the findings in the observation study of older adults and people living with dementia performing the STS movement by Dolecka et al. (2015).

Leaning forward was the most common movement strategy, used in 88.5% of the trials by the control group in this study (**Table 6.1**) compared to 100% previously reported (Dolecka et al., 2015). The foot backward strategy was observed in 34.6% of the control trials in this study compared to 33.3% reported by Dolecka et al. (2015). Other similar strategies are observed in this, and the abovementioned study with similar frequencies: pushing through knees in 46.2% and 36.6% of the control trials; no arms used in 23.1% and 20%.

Another possible chair rising strategy, the scoot forward, may also make the STW task easier (Dolecka et al., 2015, Barreca et al., 2004, Bohannon and Corrigan, 2003, Nuzik et al., 1986). However, this type of movement was not adopted by healthy older adults in previous studies in the literature (Dolecka et al., 2015). Our analysis cannot identify this strategy since the progression of the pelvis was not considered when constructing the matrices. Nevertheless, this strategy is infrequent and can be excluded if it is considered as an adjustment in the starting position of the participant. Apart from the five strategies detected, the leaning forward, foot backward, push knee, no arms and push chair, the HC of the hands progression matrix additionally revealed the arm forward strategy that wasn't previously reported in any observational studies so far.

Although there are a few studies in the literature that analysed the movement strategies of healthy individuals performing the chair rising movement (Baird and Van Emmerik, 2009, Dolecka et al., 2015, Hughes et al., 1994, Richard and Darcie, 2003, Sagawa et al., 2013), to the author's best knowledge, this is the first study that analysed the movement behaviours of patients with end-stage osteoarthritis of the knee. Therefore, no comparisons can be made regarding the frequency of the adopted strategies of this study's patient group. Nevertheless, comparing the movement preference of the control to the patient group, may offer insights on how people with chronic pain and limited lower limb function, operate.

Leaning the torso forward before seat-off, is an upper body movement strategy that was observed with similar frequencies among the control (88.5%, **Table 6.1**) and the patient (71.4%, **Table 6.1**) group. Flexing the torso results in decreasing the height of the COM from the base of support in the sagittal axis, while also increasing balance control. As a result, this movement strategy can significantly ease momentum transfer and the transition from the seating to the upright position. Contrariwise, standing up straight raises the centre of gravity above the base of support and decreases stability. Standing straight was only observed in 11.5% and 28.6% of the trials of the control and OA groups respectively.

Likewise, dragging feet posteriorly was observed with comparable frequencies among the two examined groups (34.6 and 31.4%, **Table 6.1**). This movement strategy has two potential benefits. Firstly, dragging one foot posteriorly results in a faster gait initiation by easing the transition from standing to the first swing on the walking phase. Secondly, spreading the feet increases the size of the base of support, which by extension, increases stability and the ability to move effectively.

The control of the base of support is a major contributor in postural control, body stability, and movement transitions (Inkster and Eng, 2004). Apart from widening the base of support by spreading the feet apart, adding ground contact points offer the same effect. Additional contact points can be added by using other body parts (i.e. using hands to push through the knees), or by introducing external contact points, such as a cane, a crutch, or in this case by pushing through the sides of the chair.

Pushing though the knees was observed with a non-significant difference in the frequency of use among the two groups: 46.2% and 22.9% for the control and OA participants respectively (**Table 6.1**). Yet, patients with osteoarthritis of the knee adopted the push chair strategy more frequently than the control group ($p = .015$, **Table 6.1**). The increased use of this strategy by the OA group may indicate a need to assist the STW movement by decreasing the loading on the affected knee and potentially reduce the experienced pain or discomfort. Additionally, the STW task can be a very disorienting activity, leading to transitory loss of balance and potential falls. Pushing through the chair when rising from the sitting position can help maintain balance until the seat-off phase of the movement.

Finally, the use of the arm forward strategy was very evident in the patient group (37.1%). Propelling the upper limbs anteriorly, moves the COM ahead in the sagittal plane, increasing momentum, while contributing in the rising movement by reducing the lower limb muscle output needed to complete the task.

Patients with osteoarthritis of the knee also prefer significantly more asymmetrical arm strategies (25.7%, **Table 6.3**) than the control participants do. This finding, along with an inclination towards hand assisted movements, reveal an insightful pattern in the behaviour of patients living with OA: pushing through the chair with the arm ipsilateral to the affected knee decreases the demand on lower limb extensors, while the contralateral arm may assist the movement by the use of the arm forward or push knee strategies. Such patterns might ease the pain on the affected joint by transferring the weight-bearing on other joints, increasing though, the risk of injury at the hip and ankle or the progression of the disease in other joints (Arnold et al., 2014b).

The identification of such compensation mechanisms and movement strategies may strengthen and accompany the biomechanical analysis of motion capture by providing a depiction of the manner participants perform the movement, act as an indicator of the rehabilitation process of subjects with movement disabilities, or correlate the effect of treatment methods on the outcome of the therapy. Additionally, in the occasion of a sample size with substantial variability in the biomechanics due to variations in strategy adoption, movement strategy assessment comes across as an advantageous alternative to a conventional biomechanical analysis.

7.1.2 Hierarchical clustering process

Generally, studies utilising hierarchical clustering methods, use all multiple measurements describing the population to devise a single matrix as an input for the clustering process. In past studies (Park et al., 2005, Ait El Menceur et al., 2009), the kinematic behaviours of the body's segments were used to construct a single multivariate data matrix that was used to characterize and discern goal-directed manual tasks. Nevertheless, in this thesis, data matrices were constructed for each limb, that were clustered separately from each other.

Considering different body segments independently, which in reality act in concert, has its own valuable merit. When dealing with motion capture data, it is anticipated that repeated recordings of the same participant are clustered together due to an increased resemblance of the majority of the segments behaviour. By considering each segment separately, the proposed procedure was shown to accurately discern strategies independently of the individual adopting them (**Table 6.2**). For example, Participant A (**Table 6.2**), was shown to have great variability in his/her movements; nevertheless, the proposed clustering process managed to accurately discern them. Such a feat would possibly be unattainable if we were to cluster the kinematic output of the whole body collectively.

Additionally, by only considering five body segments and identifying two to four strategies per segment, the whole-body behaviour can be described by 128 possible whole-body variations. What is more, by including further descriptive layers of movement, the suggested clustering process would exponentially increase the number of whole-body strategies, while making sure that the results are always comparable and descriptive. For example, adding the progression of the pelvis in the cluster process will increase the identification capacity of the procedure to 256 possible movement variations. Alternatively, if all body segments were clustered simultaneously, the optimum numerous cluster solution in a dendrogram would have been prohibitively challenging to detect and validate, with differences among clusters being trivial and incomparable.

To put things into perspective, 61 STW motion capture trials were submitted in four consecutive clusterings. To determine the optimum solution, agglomeration schedule coefficients and remarks from previous observational studies were used, which led to the grouping of the trials in two to three clusters per hierarchical clustering. Subsequently, to identify and label those strategies, the user had to review in Vicon Nexus, one to two trials per hierarchical clustering. As a result, 22 distinct whole-body movement strategies were identified, as seen in **Table 6.2.** On the other hand, if we were to cluster the whole-body behaviour collectively, identifying the number of different whole-body movement strategies (in this case 22), would be impossible by either using the morphology of the dendrogram or the agglomeration schedule coefficient bar chart. Furthermore, predicting the optimum number of solution is fruitily, since as explained beforehand, each population of STW trials can be characterised by up to 256 variations. Finally, associating clusters to movement strategies would require the inspection of additional trials in Vicon Nexus (in fact, in this case more than one third of the total). By clarifying these complexities, the author hopes to demonstrate the contemplation and originalities in the execution of the adopted process.

A limitation of the study may arise from the trial exclusion, resulting in an uneven distribution of the included trials among participants (**Table 6.2**). Although the strategy classification process requires the trajectories of only seven anatomical landmarks at two single time frames, entire trials had to be processed in order to facilitate the validation of the clustering results, and estimate the whole-body centre of mass trajectory which was used for the selection of frames $f1$ and $f2$. As a result, marker obstruction, more often in trials of obese participants, was the primary reason for trial exclusion.

The selection of the similarity measure and the clustering algorithm can also be viewed critically. Comprehending how these parameters work is essential for the execution of the process. One of the main reasons for this is that the clustering algorithm will work even with the most unsuitable data or clustering algorithms. The Euclidean distance as a measure of similarity between a pair of objects can be interpreted as the physical distance between two points in the Euclidean space (Everitt et al., 2010). In an example of measuring the similarity between the progressions of extremities in an axis of motion, the Euclidean distance has the fitting property that the pair of extremities with the smallest dissimilarity have moved almost equally in space. What is more, according to Borcard et al. (2011), Euclidian distance generally provides the best results among other measures of similarity when all variables are continuous. As regards the clustering algorithm, Ward's method should always be used when the data contain clusters of approximately the same size, without apparent outliers (Borcard et al., 2011). Altogether, these guidelines, suit the dichotomous nature of this study's data set, i.e. mobility impaired and healthy individuals.

7.1.3 Conclusion

In conclusion, the proposed procedure managed to classify the participants based on the combination of distinct movement techniques used to fulfil the STW movement. By means of the proposed methodology, it was possible to identify the five major strategies already reported through observation by Dolecka et al. (2015) while detecting an additional sixth, the arm forward, which was likely reported combined with the no arm used trials in the abovementioned study. Other studies either classified movement strategies through observation without quantifying the degree of progression of the participants' extremities (Dolecka et al., 2015, Bohannon and Corrigan, 2003) or set a movement distance threshold without accounting for variation due to participants' anatomy (Hughes et al., 1994). Movement classification by the proposed procedure occurs based on quantitative data and statistical calculations, classifying the studied population into clusters according to their movement preferences while taking into consideration the body segment lengths. The key advantage of this procedure is the reduced processing time of the required dataset input: instead of processing (gap filling, filtering, modelling, etc.) the entire length of each recorded trial, processing two frames suffice for the entire analysis. Matching a strategy to each cluster requires the inspection of a very small number of trials at each distinct cluster. Although the proposed classification process is not entirely free from the observational aspect, it may be employed as a practical and reliable tool to process large datasets in minimal time.

7.2 THE CAR INGRESS ASSESSMENT

7.2.1 The mock up car

A bespoke vehicle was designed and manufactured for the purposes of this study (**Chapter 5.7 The car ingress trials**). Participants' questionnaires verified that the mock up car captured the constructs of a real vehicle effectively: 85% of the people participating in the study reported that it resembles a common vehicle very accurately. This task proved to be a challenge; manufacturing a mock up car that features the architecture and basic components of a real vehicle, while permitting marker tracking, caries certain difficulties. Possible imperfections of the design lie in the absence of a dashboard and a floor slope that curves close to the pedals. Although these elements were considered at first, they were eliminated from the latest designs since it was alleged that they will obscure camera view and operation. Feasible additions for feature designs may include a handbrake, a gear lever, and a thicker window seal.

7.2.2 Movement strategy preference

One hundred-twenty trials of control and TKA participants were used for the analysis. The HC process revealed a series of strategies (**Table 6.4**) for the lower extremities (one-foot and two-foot), hands (no-, single-, and double-support), and trunk (rotated and straight). In total, seven different limb strategies, and twelve distinct whole-body movement strategies were identified.

Previous studies successfully classified the car ingress movements for the purposes of motion simulation and car ergonomics (Lu et al., 2016, Ait El Menceur et al., 2008, Lempereur et al., 2005, Chateauroux and Wang, 2010). Among those studies, two authors have used clustering approaches to classify movement techniques (Ait El Menceur et al., 2009, Lempereur et al., 2005), whereas Ait El Menceur et al. (2009) also considered three elderly participants with prostheses of the knee in a mixed population of different ages. Nevertheless, this is the first study that proceeded in the analysis of patients before and after total knee arthroplasty, and used their movement behaviour as a tool to assess their functional performance. What is more, this study proposes novelties in the execution of the clustering approach that are listed and compared with other similar studies (Ait El Menceur et al., 2009, Lempereur et al., 2005) in the upcoming section **7.2.4 Hierarchical clustering process**. As for the range and complexity of the classification outcome, this study's suggested algorithm offers excellent results. As a reference, the identification technique by Lempereur et al. (2005), suggested the existence of only two movement strategies; Chateauroux and Wang (2010) described two main car strategies and four sub strategies; Ait El Menceur et al. (2008) identified five ingress movements.

The movement preferences of this study's control group agree with similar literature reported findings. Ait El Menceur et al. (2008) worked with a single mixed population of able-bodied participants of all ages, and people with hip and knee prostheses; the authors reported that the two-foot ingress movement was adopted in 21% of the recorded trials, whereas the one-foot in 79%. These proportions are in agreement with the one-year postoperative frequencies presented in this thesis (27% and 73% for the two and one-foot strategies, respectively; **Table 6.4**). Lu et al. (2016)

reported that 14% of healthy individuals adopt the straight torso strategy, whereas the remaining 76% the rotated one. Yet again, these frequencies match the behaviour of the control population in this study: 20% and 80% for the two abovementioned torso strategies (**Table 6.4**). The hand strategies are often neglected due to the complexity of their interaction with the elements of the car. Chateauroux and Wang (2010) in a study of the car egress movement, groups the participants based on the hand interaction with the door, steering wheel, and frame, with findings comparable to those presented in the ingress car frequencies of **Table 6.4**.

We hypothesise that participants adopting the one-foot strategy are more mobile, and capable of comfortably balancing and weight bearing on a single leg. The two-foot strategy on the other hand, possibly indicates an attempt to protect the affected limb from excessive loading and potential pain or discomfort. Likewise, we assume that unsupported and single hand supported movements are opted from able-bodied participants, while double supported ingress shows a lack of balance, and an attempt to unload the lower limbs. Nevertheless, this assumption proved to be a generalization: hesitant participants struggling to maintain hand support were occasionally sorted in the unsupported movement cluster. Finally, we speculate that participants showing increased torso mobility optimise their movement in order to lessen the seat positioning phase, and swiftly, end their ingress movement in a driving position with their upper body phasing toward the steering wheel. On the other hand, less able-bodied participants would demonstrate a distinct downward ingress movement, followed by the seat positioning phase, where they rotate their pelvis and upper body anti-clockwise.

Control participants demonstrated a preference towards the one-foot (**Table 6.4**, 100%), single hand support (63%), and rotated torso strategies (80%). None of the controls used the two-foot, or the double hand-supported strategies. On the other hand, more agile control participants used the no-hand support strategy (37%) when entering the vehicle.

Patient participants' pre-operative behaviour does not reveal a profound insight into strategy preference. Nevertheless, it seems that generally, osteoarthritic patients tend to favour the same strategies control do: the most common sub strategies for this group were the one-foot (63%), single-hand support (57%) and rotated torso (57%), as were for the control group. On the other hand, post-operational behaviour clearly tends to converge more to the controls'; nevertheless, there are fluctuations in this trend throughout the post-operative visits. In detail, one-foot strategy preference was increased by 10% one year after the first visit; single-hand support increased by 23% one year after; torso-rotated strategy was similarly more frequently adopted by 10% in the same time frame. Yet, it should be noted, that even though the overall hand and torso behaviour of the year post-op and control visits show remarkable similarities, the lower limbs' linear behaviour of the control participants (100% following the one-foot strategy) remained unmatched to the patient' group performance, in every stage of their rehabilitation.

7.2.3 Time

It was assumed that both the side of the affected knee joint (left or right), and the stage of the therapy, would impact the time needed to perform the recorded task. Hypothetically, a right-side prosthesis offers a functional advantage when entering a right-hand drive car: adopting the one-foot strategy, allows participants with a right-side knee implant to keep the operated limb extended and on the ground, while the left leg will bear the demands of the task by flexing and adducting. Additionally, it was assumed that with time, the operated group will recover in terms of muscle strength and limb function. Potentially, that could lead to the transition to healthier movements, namely from two to one-foot strategies, that were hypothesised to be shorter in execution time. Finally, it was presumed that after repeated visits in the motion capture lab, the movements of the patient participants would be less hesitant, resulting is shorter times as well.

Nevertheless, these hypotheses were all proven wrong: as explained in **Chapter 6.2.2 Time,** a mixed between-within subjects ANOVA was implemented to evaluate the effect of the implant's sidedness, throughout the three visits of the TKA group, in the time needed to complete the car activity. Neither the sidedness of the affected joint ($p = .12$) nor the rehabilitation stage ($p = .19$) were found to be significant in task completion time. Additionally, there was no significant interaction between the two parameters, $p = .13$. Although non-significant, a small variation in the task completion time due to sidedness (**Table 6.6**), is still attributed to the functional advantage of a right-side prosthesis over a left one, when accessing the car.

In addition, it was also presumed that differences in body types may influence the time outcome measure. For example, taller people may need more time to position their body in the interior of the vehicle due to an unavoidable increased flexion of the torso when crossing the door frame. However, a two-way ANOVA revealed that participants' height ($p = .89$) was also non-significant in the measured time.

Finally, it was assumed that controls', and patients' one-year postoperative behaviour would converge. In fact, it was found that there was no statistical difference among the two groups ($p = .69$), verifying that task completion time is not lagging behind at the end of the patients' treatments.

7.2.4 Hierarchical clustering process

As demonstrated previously (**Chapter 7.1 The sit-to-walk assessment**), the proposed algorithm successfully utilises strategic frames of the captured movement task that enclose the variability of the participant's movements. Indicators such as centre of mass kinematics or ground reaction forces may be also used to assist the key frame identification. For this analysis, the trajectory of the centre of mass was used to identify the desirable frames. Yet, this is not an essential requirement: the trajectories of torso or pelvis markers may be used with comparable results.

To quantify the features of the movement, the author suggests using the kinematic behaviour of the segments' end-effectors. Five end-effectors were considered for the purposes of the strategy identification algorithm: the lateral malleoli, the 5^{th} metacarpals, and sternum. Additional segments (such as the pelvis or the head) may add to the complexity of the result, and the establishment of further whole-body strategies. Clustering kinematic time series can be proven a puzzling task;

in this analysis, the amplitude of the kinematic curves adequately captured movement features of the car ingress task and led to a fruitful HC.

Segmenting the body's behaviour and analysing each limb separately, constitutes a key novelty in the execution of the hierarchical clustering approach for the analysis of motion capture data. This is a significant achievement in the analysis of motion capture trials of the same participant: the same person may execute the task multiple times in a similar fashion, but with minor deviations. If the movement of the entire body was considered jointly (Ait El Menceur et al., 2009, Lempereur et al., 2005), due to the natural overall similarity in the participant's behaviour, the clustering algorithm may cluster those trials together, disregarding possible minor differences in strategy adoption. Since each segment was considered separately, the proposed procedure in this work discerned strategies independently of the participant adopting them (**Table 6.2** and **Table 6.5**). As a result, it was possible to utilise multiple recordings of the same participant, and increase the overall studied sample size. This remark, may be the reason why previous studies that worked with automated movement strategy identification, used a single trial per participant (Ait El Menceur et al., 2009, Lempereur et al., 2005). What is more, by segmenting the whole-body behaviour, it was possible to identify more movements compared to previous studies: six STW movement strategies compared to five described by Dolecka et al. (2015); twelve car ingress strategies compared to two by Lempereur et al. (2005) and five by Ait El Menceur et al. (2008).

7.2.5 Conclusion

As previously mentioned, one of the major drawbacks of the hierarchical clustering method, is that it always functions by grouping the data into clusters, irrespective of the chosen clustering algorithm, measure of similarity, or even the nature of the data. Possibly, the most challenging task when utilising such a statistical technic, is to establish that the generated clusters are meaningful for the purposes of the study. Not only that, but any results should be repeatable with any set of data, or in similar applications. One of the most important achievements of this work is that we managed to successfully and meaningfully identify and classify human behaviour as captured by means of motion capture, while guaranteeing the repeatability and functionality of the method in the analysis of various tasks: the STW and the Car ingress.

The proposed process deals with the processing time problem of motion capture data by demanding merely two frames from each trial for the clustering process. Furthermore, rather than applying the HC with all body segments behaviour simultaneously, this approach suggests considering them individually. By doing so, we were able to dichotomise the sample after each individual HC, identify a series of strategies for the considered body segments, and describe the participants' behaviour by twelve combinations of whole-body strategies. Decomposing the whole-body behaviour led to identifying strategies independently of the participant performing them (**Table 6.5**), while also permitting an easier comparison of the groups in question (**Table 6.4**).

Concentrating solely on the ingress part of the movement while ignoring the variability of the seat positioning phase, limits the range of the classification outcome. Although the seat positioning movements are anticipated to be correlated to the preceding ingress strategy, their analysis may reveal additional insight on the way people with lower limb pathologies perform the task. Even though a limitation of this approach, repeating the procedure for the positioning phase is an option.

7.3 OXFORD KNEE SCORE AND QUESTIONNAIRES

A series of questionnaires were used to access the functional improvement during activities of daily living. These questionnaires were designed to track the difficulty, tiredness, and pain levels among visits, and are presented in **APPENDIX III** and **APPENDIX IV**. Apart from the two bespoke questionnaires, the OKS (**APPENDIX I**) was used from the stuff at the Golden Jubilee National hospital during the programmed patient visits of the participating population.

We included 26 people in this analysis, 16 men and 10 women, with a mean age of 68.6 years (range, 54–79 years; STD, 5.7 years). The right knee was involved in

11 patients, and the left in the remaining 15. Mean OKS was 38.23 (STD, 6.5) before surgery and 20.73 (SD, 4.9) after surgery. Results agree to findings of similar studies with elderly subjects, before and after total knee arthroplasty surgery: in a study of 2012 (Jenny and Diesinger), a population of 200 people with a mean age of 71 years was tested. They reported that the mean OKS before surgery was 43.7 (STD, 6.9) whereas the same score after the operation was equal to 20.5 (STD, 5.6), which perfectly matches the results presented in this thesis.

A mixed between-within subjects' ANOVA was conducted to compare the effect of the implant design during the assessment period of the patient groups in the OKS clinical outcome measure. There was a statistically significant ($\mathrm{p} < .005$) improvement in the function of the patients' participants at each time point after the TKA, i.e. pre-operative vs weeks post-operative, and weeks post-operative vs a year post-operative (**Table 6.8**). Yet, it was found that the knee implant design doesn't affect the results of the OKS ($\mathrm{p} = .537$; **Figure 6.14**). This latest finding should be dealt with scepticism: although the OKS is well-suited to access knee function (Ko et al., 2009), the absence of significant floor and ceiling effect in the test may limit the ability of the accessor to detect subtle outcome differences that are not noted by patients who consider the end-results as satisfying (Jenny and Diesinger, 2012). Additional statistical tests demonstrated that there is no correlation between movement habits and the OKS (**Table 6.9**). The three-way ANOVA incorporated data from all three patients visits. Even though the OKS indicates a significant improvement in the patients' function at each pairwise comparison after the TKA, it seems that participants who scored better in the self-reported measures do not adopt different movement patterns than those who scored poorly. This finding can either imply that movement strategy identification is not fit to evaluate functional performance, or in fact, it is more sensitive than the OKS. That might be more apparent if the questions contained within the OKS are reviewed with scepticism: more than half of the questionnaire is dealing with pain levels and joint stability (**APPENDIX I – Oxford knee score**). As a result, it is expected that participants revealed of pain will score higher; nevertheless, that doesn't necessary indicates an improvement in joint function. Thus, it may be more productive to treat movement strategy habits and transitions complementary to patient reported outcome measures.

Patient questionnaires were also in agreement with the OKS results, showing a continues improvement in the reported pain levels during the entire rehabilitation process ($p < .001$). Furthermore, the difficulty to perform activities of daily living seems to decline significantly a year after the operation ($p = .017$). Nevertheless, it appears that TKA does not make activities of daily living less tiring. However, it should be noted that participants did not find the examined activities of daily living tiring to begin with: 96% of the examined population found the first motion capture session to be very little or no tiring at all (**Table 6.10**).

Similarly to the OKS questionnaires, patient questionnaires were not able to detect an effect of the knee implant design in the perceived difficulty, pain, and tiredness levels (**Table 6.11**). This may indicate that patients prior to operation rate their knee condition as very severe, and fail to evaluate their improvement post-surgically after a successful operation. The use of more thorough tests would help to perform a more comprehensive investigation of performance after TKA surgery.

CHAPTER 8. SUMMARY

8.1 THE SIT-TO-WALK ASSESSMENT

Patients with osteoarthritis of the knee, commonly alter their movement to compensate for lower limb weakness. Movement alterations may lead to weight-bearing asymmetries, and potentially in the progression of the disease in other joints of the lower extremities. This study presents a novel numerical procedure for the identification of sit-to-walk movement strategies and asymmetries between OA and control groups.

Ten control and twelve OA participants performed the STW task in a motion capture laboratory. Participants sat on a stool, height adjusted to 100% of their knee height, then stood, and walked to pick up an object from a table in front of them. Different movement strategies were identified by means of hierarchical clustering. Trials were also classified as to whether the left and right extremities used a bilateral or an asymmetrical strategy. OA patients used significantly more asymmetrical arm strategies ($p = .034$), while adopting the pushing through the chair strategy more often than the control participants ($p = .015$).

The results demonstrated that control and OA participants favour different STW strategies. The OA patients’ arm behaviour possibly indicates compensation for weakness of the affected leg. The proposed statistical procedure may be useful to rapidly assess post-operative outcomes and developing rehabilitation strategies.

8.2 THE CAR INGRESS ASSESSMENT

This study describes an alternative movement identification technique for the analysis of the ingress movement, in order to evaluate changes in the movement behaviour of patients after total knee arthroplasty surgery in comparison to healthy age-matched control participants.

A mock-up car was fabricated based on the architecture of a common vehicle design. Ten control participants and ten patients with severe osteoarthritis of the knee attended a single and three motion capture session(s) respectively. Driver's seat and door positioning were adjusted prior to the recording. Participants were asked to enter the car and sit comfortably adopting a driving position. Three trials per session were used for the identification of movement strategies by means of hierarchical clustering. The time to task completion was also measured.

Results demonstrated that control participants favour different movement strategies compared to the pre-operational behavior of the patients with osteoarthritis. Post-operational behaviour tends to converge to the controls' performance. Group membership, height and sidedness of the affected joint were found to be non-significant in task completion time.

8.3 OXFORD KNEE SCORE AND QUESTIONNAIRES

Patient filled quality-of-life questionnaires are a vital tool for the assessment of clinical outcomes, as they depict patient satisfaction. The Oxford Knee Score is a validated instrument that is extensively used to measure outcomes of TKA operations.

Twenty-six patients were included in this analysis. Eligible patient volunteers were suitable to receive any of three knee implant designs. The OKS questionnaire along with a bespoke questionnaire was handed to each participant prior to surgical procedure, and twice during follow-up visits. The mean OKS were 38.2 (range, 23–49; SD, 6.6) before surgery, 28.5 (range, 15–39; SD, 7.3) and 20.7 (range, 13–33; SD, 4.9) two months and a year after surgery, respectively. Patients reported a significant improvement in their self-assessment ($p < .005$), but no differences were observed due to knee implant allocation. Patient questionnaires that were given after each motion capture session were in agreement with the OKS results, showing a continuous improvement in the reported pain and difficulty levels during their therapy. There was also no statistically significant interaction between strategy adoption and the OKS results.

8.4 REVIEW OF THE AIMS OF THE STUDY

The aim of the study was to compare the biomechanical performance of three knee replacements with different bearing designs (UC, CR DD, UCR) to that of a natural knee. The performance of the studied population was measured using motion capture analysis, and a series of questionnaires such as the Oxford Knee Score. The motion capture data were analysed by means of a statistical procedure called hierarchical clustering, which to the author's knowledge, is implemented for the first time in literature for the assessment of persons with clinical impairments. Outcome measures among groups were analysed statistically using ANOVAs, Friedman, Kruskal-Wallis H, Wilcoxon, Chi-square and Fisher's exact tests.

The aim of the study was to determine which type of bearing provides better function in daily living. Participants were tested in two of the most challenging activities of daily living, the sit-to-walk and the car ingress tasks. Currently, the author of this work was unable to fully determine the existence of any potential differences among patient groups. This is due to the fact, that by the time this thesis was completed, only twelve full sets of patient data (i.e. from patients who attended all three motion capture visits) where recorded in the Biomedical Engineering department of the University of Strathclyde. From those twelve data sets, ten were fully used in the analysis of the car ingress task presented in this thesis. Even with these few recordings, knee design comparison was impractical: out of the ten patients that were considered, seven were randomised to receive the same knee implant, leaving little space for substantial comparisons among groups. As a result, the hypothesis (**1.2 Aims of the study**) that the mobile bearing can provide closer function to that of the native knee, can neither be accepted or rejected.

On the other hand, movement strategy identification which was the principal objective of this work, was proven to be an excellent tool to deal with the second and third aims of the study: determining improvement in function postoperatively, and identifying differences among groups. Movement behaviour classification verified the improvement in knee function postoperatively, when compared to the preoperative assessment. What is more, the behaviour of the patient groups one year postoperatively was shown to significantly converge to the controls'.

Finally, the last objective of the study was to compare Oxford knee scores, and patient performance with the use of questionnaires. Data from all 26 people who completed the OKS assessment in the Golden Jubilee national hospital were used. OKS and bespoke questionnaires indeed verified a significant functional improvement in the self-assessment of the participating osteoarthritic population. Nevertheless, questionnaire outcomes were considered to be insufficient to reveal differences due to knee implant allocation.

8.5 RECOMMENDATIONS FOR FUTURE WORK

As previously mentioned, the existing evidence on whether bearing design affects the functional performance after TKA is unclear. Certainly, this may simply mean that implant architecture does not significantly affect the outcomes of the operation. Yet, if that's not the case, there are two underlying issues that might be accountable for this ambiguity: either the functional tests we are conducting are not demanding enough to expose antitheses, or there are other factors affecting the operational outcome that are not controlled or even monitored.

The counterargument in the first case is that elderly people with severe OA, which is generally accompanied by muscle atrophy, narrow their activity levels to a relative minimum, while only carrying out plain everyday tasks such as walking, stair climbing, standing from a seated position, etc. Thus, recreating more demanding tasks (e.g. running or cycling) just for the sake of exposing differences due to bearing design is purposeless.

On the other hand, there is an abundant of clinical and technical issues that affect the outcome of total knee replacement; along these lines, the root of our uncertainty may stem from an inability to regulate factors generating variability in a research environment. For example, it has been repeatedly shown that good pre-operative knee function largely results in better postoperative outcomes (Sugitani et al., 2015, Clement, 2013, Sancheti et al., 2013, Farahini et al., 2012, Kawamura and Bourne, 2001). Other factors accountable for the quality of the surgical results are the general physical health of the patient (Clement, 2013), obesity and other comorbidities (Dooley and Secretan, 2016, Moon et al., 2008), component mal-alignment and surgeon performance (Gatti et al., 2014), physiotherapy (Lowe et al., 2007), and knee anatomy (e.g. patellar tilt angle) (Kawamura and Bourne, 2001).

Hence, future studies should attempt not to increase sample size, but single out participants in a thorough manner by taking into consideration as many outcome affecting factors as possible. For example, parameters such as muscle mass, condition of the cruciate ligaments, knee range of motion, general health, age, activity levels, obesity, knee anatomy, and patient post-operational expectation should be taken under consideration for participant recruitment or group allocation. What is more, surgical operations and rehabilitation should be carried out by the same surgical team and physiotherapist respectively, while medical imaging should be used to ensure consistent implant alignment for all sample size. In this way, a research study with only few participants may be more adequate to discuss the controversiality between fixed and mobile knee bearings.

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APPENDIX I – OXFORD KNEE SCORE

During the past 4 weeks……

1. How would you describe the pain you usually have in your knee?

- ○ None
- ○ Very mild
- ○ Mild
- ○ Moderate
- ○ Severe

2. Have you had any trouble washing and drying yourself (all over) because of your knee?

- ○ No trouble at all
- ○ Very little trouble
- ○ Moderate trouble
- ○ Extreme difficulty
- ○ Impossible to do

3. Have you had any trouble getting in and out of the car or using public transport because of your knee? (With or without a stick)

- ○ No trouble at all
- ○ Very little trouble
- ○ Moderate trouble
- ○ Extreme difficulty
- ○ Impossible to do

7. Could you kneel down and get up again afterwards?

- ○ Yes, easily
- ○ With little difficulty
- ○ With moderate difficulty
- ○ With extreme difficulty
- ○ No, impossible

8. Are you troubled by pain in your knee at night in bed?

- ○ Not at all
- ○ Only one or two nights
- ○ Some nights
- ○ Most nights
- ○ Every night

9. How much has pain from your knee interfered with your usual work? (including housework)

- ○ Not at all
- ○ A little bit
- ○ Moderately
- ○ Greatly
- ○ Totally

4. For how long are you able to walk before the pain in your knee becomes severe? (With or without a stick)

- No pain > 60 min
- 16 - 60 minutes
- 5 - 15 minutes
- Around the house only
- Not at all - severe on walking

5. After a meal (sat at a table), how painful has it been for you to stand up from a chair because of your knee?

- Not at all painful
- Slightly painful
- Moderately pain
- Very painful
- Unbearable

6. Have you been limping when walking, because of your knee?

- Rarely / never
- Sometimes or just at first
- Often, not just at first
- Most of the time
- All of the time

10. Have you felt that your knee might suddenly give away or let you down?

- Rarely / Never
- Sometimes or just at first
- Often, not at first
- Most of the time
- All the time

11. Could you do household shopping on your own?

- Yes, easily
- With little difficulty
- With moderate difficulty
- With extreme difficulty
- No, impossible

12. Could you walk down a flight of stairs?

- Yes, easily
- With little difficulty
- With moderate difficulty
- With extreme difficulty
- No, impossible

Score 0 to 19	May indicate severe knee arthritis. It is highly likely that you may well require some form of surgical intervention, contact your family physician for a consult with an Orthopaedic Surgeon.
Score 20 to 29	May indicate moderate to severe knee arthritis. See your family physician for an assessment and x-ray. Consider a consult with an Orthopaedic Surgeon.
Score 30 to 39	May indicate mild to moderate knee arthritis. Consider seeing your family physician for an assessment and possible x-ray. You may benefit from non-surgical treatment, such as exercise, weight loss, and /or anti-inflammatory medication
Score 40 to 48	May indicate satisfactory joint function. May not require any formal treatment.

APPENDIX II – MOCK UP CAR DRAWINGS

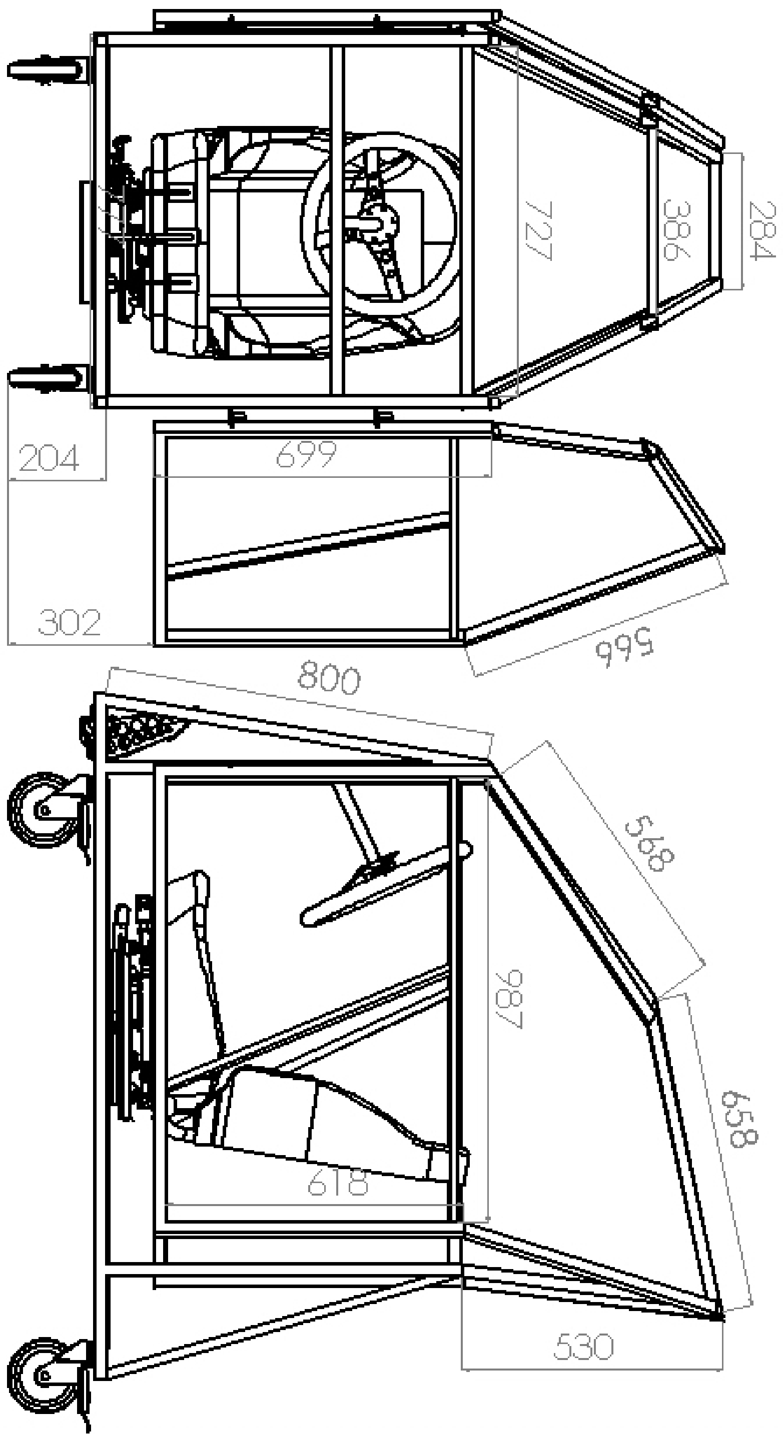

Figure A.0.1 Car measurements

Figure A.0.2 Mock up car, front view

Figure A.0.3 The door locking mechanism.

Figure A.0.4 The steering wheel and pedals.

APPENDIX III – SIT-TO-WALK QUESTIONNAIRE

4) Did you have any difficulty during the task?				
No difficulty at all	Very little difficulty	Moderate difficulty	Extreme difficulty	Impossible to do

5) How would you describe any pain felt during the task?				
None	Very mild	Mild	Moderate	Severe

6) Was the task tiring for you?				
Not tiring at all	Slightly tiring	Moderately tiring	Extremely tiring	Impossible to do

Do you have any other comments?

APPENDIX IV – CAR INGRESS QUESTIONNAIRE

1) Did you have any difficulty during the task?				
No difficulty at all	Very little difficulty	Moderate difficulty	Extreme difficulty	Impossible to do

2) How would you describe any pain felt during the task?				
None	Very mild	Mild	Moderate	Severe

3) Was the task tiring for you?				
Not tiring at all	lightly tiring	Moderately tiring	Extremely tiring	Impossible to do

4) Do you use a car?	
Yes	No

5) Have you had any difficulty getting in and out of a car because of your knee? (With or without a walking aid)				
No difficulty at all	Very little difficulty	Moderate difficulty	Extreme difficulty	Impossible to do

6) Other than the appearance, do you think that the mock up car in our laboratory resembles a common car (space, height, seats, ease to get in and out, etc.)?				
Yes, very accurately	Yes, to some extent	Not sure	No, not that much	No, not at all

If no, please say why:

7) Do you think that this task resembles your experience entering and exiting your car?				
Yes, very accurately	Yes, to some extent	Not sure	No, not that much	No, not at all

Do you have any other comments?

APPENDIX V – PARTICIPANT CONSENT FORM

Consent Form for Participants

Name of department: Biomedical Engineering

Title of the study: Clinical investigation of the functional outcomes of high congruency versus low congruency knee bearings.

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences.
- I understand that I can withdraw my data from the study at any time without giving reason.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I understand that whether I participate in the project or not will in no way affect my standing within the University of Strathclyde.
- I confirm that I meet the inclusion/exclusion criteria.
- I consent to being a participant in the project and for the collection, documentation and usage of data gathered during the experiment.
- I understand that incentives/reimbursements will not be offered for participation.

Optional:

- I consent to the use of unidentifiable audio and video data recorded as part of the project for educational purposes
- I consent to the use of unidentifiable audio and video data recorded as part of the project in future publications [delete which is not being used]. Yes/ No

Full Name of Participant:	
Signature of Participant:	Date:

APPENDIX VI – MATLAB SCRIPT

```
close all force;
clear all;
clc;
tic % starts timer;
%Simple GUI function selection;
choice = menu('Choose a function','1. Torso Flexion (y)','2. Feet Movement (x)','3. Hands Movement (x)','4. Hands Position (xyz)','5. Feet Movement (xyz)','6. Hands Movement (xyz)','7.Torso Rotation (xyz)','8.Head Rotation (xyz)');
attributes = 'Trajectories';
% Processing waitbar
h=waitbar(0,'Please wait...','Name','Progress','CreateCancelBtn','setappdata(gcbf,''canceling'',1)');
setappdata(h,'canceling',0);
% Reads file containing particinapt's heights;
[num_height,txt_height,raw_height] = xlsread('HEIGHTS.xlsx');
% Changes directory;
cd('data_csv_files');
i=0;
j=0;
trial_num=1;
patient_num=1;
% Loads csv files from directory;
csvfiles = dir('*.csv');
% Loops 1 by 1 each file;
for file = csvfiles';
i=i+1;
[num{i},txt{i},raw{i}] = xlsread(file.name);
cur_name{i}=lower(file.name(1:6));
if ((i>=2) && strcmp(cur_name{i},cur_name{i-1})==1);
char_label=char(j+'A'-1);
trial_num=trial_num+1;
else;
```

```
j=j+1;
char_label=char(j+'A'-1);
trial_num=1;
end;;
% Finds height based on participant's name
[rh,ch] = find(not(cellfun('isempty', strfind(lower(txt_height), cur_name{i}))));
h=num_height(rh(1,1)-6);
% Converts numeric to cell array;
num_cell{i}=num2cell(num{i});
if choice==1;
%-------------------- Torso Flexion (y) function --------------------------------%
[r1,c1] = find(not(cellfun('isempty', strfind(txt{i}, 'CLAV'))));
Z_STRN_start=num_cell{i}{r1+2,c1+2};
Z_STRN_last =num_cell{i}{end,c1+2};
X_STRN_start=num_cell{i}{r1+2,c1};
X_STRN_last =num_cell{i}{end,c1};
SN{1,i}=['YEAR-',char_label,num2str(trial_num),' - ',cur_name{i}];
SN{2,i}=(atand((Z_STRN_start-Z_STRN_last)/(X_STRN_start-X_STRN_last)));
elseif choice==2;
%-------------------- Feet Movement (x) --------------------------------%
[r2_r,c2_r] = find(not(cellfun('isempty', strfind(txt{i}, 'RANK'))));
X_RANK_start=num_cell{i}{r2_r+2,c2_r};
X_RANK_last =num_cell{i}{end,c2_r};
LM_r{1,i}=['YEAR-',char_label,num2str(trial_num),'R - ',cur_name{i}];
LM_r{2,i}=(X_RANK_start-X_RANK_last)*(1/h)*1000;
[r2_l,c2_l] = find(not(cellfun('isempty', strfind(txt{i}, 'LANK'))));
X_LANK_start=num_cell{i}{r2_l+2,c2_l};
X_LANK_last=num_cell{i}{end,c2_l};
LM_l{1,i}=['YEAR-',char_label,num2str(trial_num),'L - ',cur_name{i}];
LM_l{2,i}=(X_LANK_start-X_LANK_last)*(1/h)*1000;
elseif choice==3;
%-------------------- Hands Movement (x) ---------------------------------%
[r3_r,c3_r] = find(not(cellfun('isempty', strfind(txt{i}, 'RFIN'))));
X_RFIN_start=num_cell{i}{r3_r+2,c3_r};
X_RFIN_last =num_cell{i}{end,c3_r};
M_r{1,i}=['YEAR-',char_label,num2str(trial_num),'R - ',cur_name{i}];
```

```
M_r{2,i}=(X_RFIN_start-X_RFIN_last)*(1/h)*1000;
[r3_l,c3_l] = find(not(cellfun('isempty', strfind(txt{i}, 'LFIN'))));
X_LFIN_start=num_cell{i}{r3_l+2,c3_l};
X_LFIN_last =num_cell{i}{end,c3_l};
M_l{1,i}=['YEAR-',char_label,num2str(trial_num),'L - ',cur_name{i}];
M_l{2,i}=(X_LFIN_start-X_LFIN_last)*(1/h)*1000;
elseif choice==4;
%-------------------- Hands Position rel. to the Knees (xyz) ---------------------------------%
[r4_rf_x,c4_rf_x] = find(not(cellfun('isempty', strfind(txt{i}, 'RFIN'))));
X_RFIN_last =num_cell{i}{end,c4_rf_x};
[r4_rk_x,c4_rk_x] = find(not(cellfun('isempty', strfind(txt{i}, 'RKNE'))));
X_RKNE_last =num_cell{i}{end,c4_rk_x};
SM_1r{1,i}=['YEAR-',char_label,num2str(trial_num),'R - ',cur_name{i}];
SM_1r{2,i}=(X_RFIN_last-X_RKNE_last)*(1/h)*1000;
[r4_lf_x,c4_lf_x] = find(not(cellfun('isempty', strfind(txt{i}, 'LFIN'))));
X_LFIN_last =num_cell{i}{end,c4_lf_x};
[r4_lk_x,c4_lk_x] = find(not(cellfun('isempty', strfind(txt{i}, 'LKNE'))));
X_LKNE_last =num_cell{i}{end,c4_lk_x};
SM_1l{1,i}=['YEAR-',char_label,num2str(trial_num),'L - ',cur_name{i}];
SM_1l{2,i}=(X_LFIN_last-X_LKNE_last)*(1/h)*1000;
[r4_rf_y,c4_rf_y] = find(not(cellfun('isempty', strfind(txt{i}, 'RFIN'))));
Y_RFIN_last =num_cell{i}{end,c4_rf_y+1};
[r4_rk_y,c4_rk_y] = find(not(cellfun('isempty', strfind(txt{i}, 'RKNE'))));
Y_RKNE_last =num_cell{i}{end,c4_rk_y+1};
SM_2r{1,i}=['YEAR-',char_label,num2str(trial_num),'R - ',cur_name{i}];
SM_2r{2,i}=(Y_RFIN_last-Y_RKNE_last)*(1/h)*1000;
[r4_lf_y,c4_lf_y] = find(not(cellfun('isempty', strfind(txt{i}, 'LFIN'))));
Y_LFIN_last =num_cell{i}{end,c4_lf_y+1};
[r4_lk_y,c4_lk_y] = find(not(cellfun('isempty', strfind(txt{i}, 'LKNE'))));
Y_LKNE_last =num_cell{i}{end,c4_lk_y+1};
SM_2l{1,i}=['YEAR-',char_label,num2str(trial_num),'L - ',cur_name{i}];
SM_2l{2,i}=(Y_LKNE_last-Y_LFIN_last)*(1/h)*1000;
[r4_rf_z,c4_rf_z] = find(not(cellfun('isempty', strfind(txt{i}, 'RFIN'))));
Z_RFIN_last =num_cell{i}{end,c4_rf_z+2};
[r4_rk_z,c4_rk_z] = find(not(cellfun('isempty', strfind(txt{i}, 'RKNE'))));
Z_RKNE_last =num_cell{i}{end,c4_rk_z+2};
```

```
SM_3r{1,i}=['YEAR-',char_label,num2str(trial_num),'R - ',cur_name{i}];
SM_3r{2,i}=(Z_RFIN_last-Z_RKNE_last)*(1/h)*1000;
[r4_lf_z,c4_lf_z] = find(not(cellfun('isempty', strfind(txt{i}, 'LFIN'))));
Z_LFIN_last =num_cell{i}{end,c4_lf_z+2};
[r4_lk_z,c4_lk_z] = find(not(cellfun('isempty', strfind(txt{i}, 'LKNE'))));
Z_LKNE_last =num_cell{i}{end,c4_lk_z+2};
SM_3l{1,i}=['YEAR-',char_label,num2str(trial_num),'L - ',cur_name{i}];
SM_3l{2,i}=(Z_LFIN_last-Z_LKNE_last)*(1/h)*1000;
elseif choice==5;
%--------------------  Feet Movement (xyz) --------------------------------%
[r5_r,c5_r] = find(not(cellfun('isempty', strfind(txt{i}, 'RANK'))));
X_RANK_start=num_cell{i}{r5_r+2,c5_r};
X_RANK_last =num_cell{i}{end,c5_r};
Y_RANK_start=num_cell{i}{r5_r+2,c5_r+1};
Y_RANK_last =num_cell{i}{end,c5_r+1};
Z_RANK_start=num_cell{i}{r5_r+2,c5_r+2};
Z_RANK_last =num_cell{i}{end,c5_r+2};
LMXYZ{1,i}=['YEAR-',char_label,num2str(trial_num),'-',cur_name{i}];
LMXYZ{2,i}=(X_RANK_start-X_RANK_last)*(1/h)*1000;
LMXYZ{3,i}=(Y_RANK_start-Y_RANK_last)*(1/h)*1000;
LMXYZ{4,i}=(Z_RANK_start-Z_RANK_last)*(1/h)*1000;
[r5_l,c5_l] = find(not(cellfun('isempty', strfind(txt{i}, 'LANK'))));
X_LANK_start=num_cell{i}{r5_l+2,c5_l};
X_LANK_last =num_cell{i}{end,c5_l};
Y_LANK_start=num_cell{i}{r5_l+2,c5_l+1};
Y_LANK_last =num_cell{i}{end,c5_l+1};
Z_LANK_start=num_cell{i}{r5_l+2,c5_l+2};
Z_LANK_last =num_cell{i}{end,c5_l+2};
LMXYZ{5,i}=(X_LANK_start-X_LANK_last)*(1/h)*1000;
LMXYZ{6,i}=(Y_LANK_start-Y_LANK_last)*(1/h)*1000;
LMXYZ{7,i}=(Z_LANK_start-Z_LANK_last)*(1/h)*1000;
elseif choice==6;
%--------------------  Hands Movement (xyz) --------------------------------%
[r6_r,c6_r] = find(not(cellfun('isempty', strfind(txt{i}, 'RFIN'))));
X_RFIN_start=num_cell{i}{r6_r+2,c6_r};
X_RFIN_last =num_cell{i}{end,c6_r};
```

```
Y_RFIN_start=num_cell{i}{r6_r+2,c6_r+1};
Y_RFIN_last =num_cell{i}{end,c6_r+1};
Z_RFIN_start=num_cell{i}{r6_r+2,c6_r+2};
Z_RFIN_last =num_cell{i}{end,c6_r+2};
MXYZ_r{1,i}=['YEAR-',char_label,num2str(trial_num),'R-',cur_name{i}];
MXYZ_r{2,i}=(X_RFIN_start-X_RFIN_last)*(1/h)*1000;
MXYZ_r{3,i}=(Y_RFIN_start-Y_RFIN_last)*(1/h)*1000;
MXYZ_r{4,i}=(Z_RFIN_start-Z_RFIN_last)*(1/h)*1000;
[r6_l,c6_l] = find(not(cellfun('isempty', strfind(txt{i}, 'LFIN'))));
X_LFIN_start=num_cell{i}{r6_l+2,c6_l};
X_LFIN_last =num_cell{i}{end,c6_l};
Y_LFIN_start=num_cell{i}{r6_l+2,c6_l+1};
Y_LFIN_last =num_cell{i}{end,c6_l+1};
Z_LFIN_start=num_cell{i}{r6_l+2,c6_l+2};
Z_LFIN_last =num_cell{i}{end,c6_l+2};
MXYZ_l{1,i}=['YEAR-',char_label,num2str(trial_num),'L-',cur_name{i}];
MXYZ_l{2,i}=(X_LFIN_start-X_LFIN_last)*(1/h)*1000;
MXYZ_l{3,i}=(Y_LFIN_start-Y_LFIN_last)*(1/h)*1000;
MXYZ_l{4,i}=(Z_LFIN_start-Z_LFIN_last)*(1/h)*1000;
elseif choice==7;
%--------------------  Torso Rotation (xyz) function --------------------------------%
[r7,c7] = find(not(cellfun('isempty', strfind(txt{i}, 'C7'))));
X_C7_start=num_cell{i}{r7+2,c7};
X_C7_last =num_cell{i}{end,c7};
Y_C7_start=num_cell{i}{r7+2,c7+1};
Y_C7_last =num_cell{i}{end,c7+1};
Z_C7_start=num_cell{i}{r7+2,c7+2};
Z_C7_last =num_cell{i}{end,c7+2};
X_CLAV_start=num_cell{i}{r7+2,c7+6};
X_CLAV_last =num_cell{i}{end,c7+6};
Y_CLAV_start=num_cell{i}{r7+2,c7+7};
Y_CLAV_last =num_cell{i}{end,c7+7};
Z_CLAV_start=num_cell{i}{r7+2,c7+8};
Z_CLAV_last =num_cell{i}{end,c7+8};
X_STRN_start=num_cell{i}{r7+2,c7+9};
X_STRN_last =num_cell{i}{end,c7+9};
```

```
Y_STRN_start=num_cell{i}{r7+2,c7+10};
Y_STRN_last =num_cell{i}{end,c7+10};
Z_STRN_start=num_cell{i}{r7+2,c7+11};
Z_STRN_last =num_cell{i}{end,c7+11};
TORSO{1,i}=['YEAR-',char_label,num2str(trial_num),' - ',cur_name{i}];
TORSO{2,i}=(atand((Y_CLAV_start-Y_STRN_start)/(Z_CLAV_start-Z_STRN_start)))-
    (atand((Y_CLAV_last-Y_STRN_last)/(Z_CLAV_last-Z_STRN_last)));
TORSO{3,i}=(atand((X_CLAV_start-X_STRN_start)/(Z_CLAV_start-Z_STRN_start)))-
    (atand((X_CLAV_last-X_STRN_last)/(Z_CLAV_last-Z_STRN_last)));
TORSO{4,i}=(atand((Y_CLAV_start-Y_C7_start)/(X_CLAV_start-X_C7_start)))-
    (atand((Y_CLAV_last-Y_C7_last)/(X_CLAV_last-X_C7_last)));
elseif choice==8;
%--------------------  Head Rotation (xyz) function --------------------------------%
[r8,c8] = find(not(cellfun('isempty', strfind(txt{i}, 'LFHD'))));
X_LFHD_last =num_cell{i}{end,c8};
Y_LFHD_last =num_cell{i}{end,c8+1};
Z_LFHD_last =num_cell{i}{end,c8+2};
X_RFHD_last =num_cell{i}{end,c8+3};
Y_RFHD_last =num_cell{i}{end,c8+4};
Z_RFHD_last =num_cell{i}{end,c8+5};
X_LBHD_last =num_cell{i}{end,c8+6};
Y_LBHD_last =num_cell{i}{end,c8+7};
Z_LBHD_last =num_cell{i}{end,c8+8};
X_RBHD_last =num_cell{i}{end,c8+9};
Y_RBHD_last =num_cell{i}{end,c8+10};
Z_RBHD_last =num_cell{i}{end,c8+11};
X_HD_last =(X_LFHD_last+X_RFHD_last+X_LBHD_last+X_RBHD_last)/4;
Y_HD_last =(Y_LFHD_last+Y_RFHD_last+Y_LBHD_last+Y_RBHD_last)/4;
Z_HD_last =(Z_LFHD_last+Z_RFHD_last+Z_LBHD_last+Z_RBHD_last)/4;
X_FHD_last =(X_LFHD_last+ X_RFHD_last)/2;
Y_FHD_last =(Y_LFHD_last+ Y_RFHD_last)/2;
Z_FHD_last =(Z_LFHD_last+ Z_RFHD_last)/2;
X_BHD_last =(X_LBHD_last+ X_RBHD_last)/2;
Y_BHD_last =(Y_LBHD_last+ Y_RBHD_last)/2;
Z_BHD_last =(Z_LBHD_last+ Z_RBHD_last)/2;
X_LFHD_start =num_cell{i}{r8+2,c8};
```

207.Y_LFHD_start =num_cell{i}{r8+2,c8+1};

208.Z_LFHD_start =num_cell{i}{r8+2,c8+2};

209.X_RFHD_start =num_cell{i}{r8+2,c8+3};

210.Y_RFHD_start =num_cell{i}{r8+2,c8+4};

211.Z_RFHD_start =num_cell{i}{r8+2,c8+5};

212.X_LBHD_start =num_cell{i}{r8+2,c8+6};

213.Y_LBHD_start =num_cell{i}{r8+2,c8+7};

214.Z_LBHD_start =num_cell{i}{r8+2,c8+8};

215.X_RBHD_start =num_cell{i}{r8+2,c8+9};

216.Y_RBHD_start =num_cell{i}{r8+2,c8+10};

217.Z_RBHD_start =num_cell{i}{r8+2,c8+11};

218.X_HD_start =(X_LFHD_start+X_RFHD_start+X_LBHD_start+X_RBHD_start)/4;

219.Y_HD_start =(Y_LFHD_start+Y_RFHD_start+Y_LBHD_start+Y_RBHD_start)/4;

220.Z_HD_start =(Z_LFHD_start+Z_RFHD_start+Z_LBHD_start+Z_RBHD_start)/4;

221.X_FHD_start =(X_LFHD_start+ X_RFHD_start)/2;

222.Y_FHD_start =(Y_LFHD_start+ Y_RFHD_start)/2;

223.Z_FHD_start =(Z_LFHD_start+ Z_RFHD_start)/2;

224.X_BHD_start =(X_LBHD_start+ X_RBHD_start)/2;

225.Y_BHD_start =(Y_LBHD_start+ Y_RBHD_start)/2;

226.Z_BHD_start =(Z_LBHD_start+ Z_RBHD_start)/2;

227.X_C7_last =num_cell{i}{end,c8+12};

228.Y_C7_last =num_cell{i}{end,c8+13};

229.Z_C7_last =num_cell{i}{end,c8+14};

230.X_CLAV_last =num_cell{i}{end,c8+18};

231.Y_CLAV_last =num_cell{i}{end,c8+19};

232.Z_CLAV_last =num_cell{i}{end,c8+20};

233.X_N_last =(X_C7_last+ X_CLAV_last)/2;

234.Y_N_last =(Y_C7_last+ Y_CLAV_last)/2;

235.Z_N_last =(Z_C7_last+ Z_CLAV_last)/2;

236.X_C7_start =num_cell{i}{r8+2,c8+12};

237.Y_C7_start =num_cell{i}{r8+2,c8+13};

238.Z_C7_start =num_cell{i}{r8+2,c8+14};

239.X_CLAV_start =num_cell{i}{r8+2,c8+18};

240.Y_CLAV_start =num_cell{i}{r8+2,c8+19};

241.Z_CLAV_start =num_cell{i}{r8+2,c8+20};

242.X_N_start =(X_C7_start+ X_CLAV_start)/2;

```
Y_N_start =(Y_C7_start+ Y_CLAV_start)/2;
Z_N_start =(Z_C7_start+ Z_CLAV_start)/2;
HEAD{1,i}=['YEAR-',char_label,num2str(trial_num),' - ',cur_name{i}];
HEAD{2,i}=(atand((Y_HD_start-Y_N_start)/(Z_HD_start-Z_N_start)))-(atand((Y_HD_last-Y_N_last)/(Z_HD_last-Z_N_last)));
HEAD{3,i}=(atand((X_HD_start-X_N_start)/(Z_HD_start-Z_N_start)))-(atand((X_HD_last-X_N_last)/(Z_HD_last-Z_N_last)));
HEAD{4,i}=(atand((X_FHD_start-X_BHD_start)/(Y_FHD_start-Y_BHD_start)))-(atand((X_FHD_last-X_BHD_last)/(Y_FHD_last-Y_BHD_last)));
end;
% Updates the waitbar;
waitbar(i / length(csvfiles'));
end;
set(0,'ShowHiddenHandles','on');
delete(get(0,'Children'));
cd('../');
%% Exports;
if choice==1;
xlswrite('results/YEAR-Torso.xls',SN');
elseif choice==2;
LM(1,1:length(csvfiles'))=LM_l(1,1:length(csvfiles'));
LM(2,1:length(csvfiles'))=LM_l(2,1:length(csvfiles'));
LM(1,length(csvfiles')+1:2*length(csvfiles'))=LM_r(1,1:length(csvfiles'));
LM(2,length(csvfiles')+1:2*length(csvfiles'))=LM_r(2,1:length(csvfiles'));
xlswrite('results/YEAR-Feet.xls',LM');
elseif choice==3;
M(1,1:length(csvfiles'))=M_l(1,1:length(csvfiles'));
M(2,1:length(csvfiles'))=M_l(2,1:length(csvfiles'));
M(1,length(csvfiles')+1:2*length(csvfiles'))=M_r(1,1:length(csvfiles'));
M(2,length(csvfiles')+1:2*length(csvfiles'))=M_r(2,1:length(csvfiles'));
xlswrite('results/YEAR-Hands.xls',M');
elseif choice==4;
SM(1,1:length(csvfiles'))=SM_1l(1,1:length(csvfiles'));
SM(1,length(csvfiles')+1:2*length(csvfiles'))=SM_1r(1,1:length(csvfiles'));
SM(2,1:length(csvfiles'))=SM_1l(2,1:length(csvfiles'));
SM(2,length(csvfiles')+1:2*length(csvfiles'))=SM_1r(2,1:length(csvfiles'));
```

```
SM(3,1:length(csvfiles'))=SM_2l(2,1:length(csvfiles'));
SM(3,length(csvfiles')+1:2*length(csvfiles'))=SM_2r(2,1:length(csvfiles'));
SM(4,1:length(csvfiles'))=SM_3l(2,1:length(csvfiles'));
SM(4,length(csvfiles')+1:2*length(csvfiles'))=SM_3r(2,1:length(csvfiles'));
xlswrite('results/YEAR-Hands(pos).xls',SM');
elseif choice==5;
xlswrite('results/YEAR-Feet(xyz).xls',LMXYZ');
elseif choice==6;
MXYZ(1,1:length(csvfiles'))=MXYZ_l(1,1:length(csvfiles'));
MXYZ(2,1:length(csvfiles'))=MXYZ_l(2,1:length(csvfiles'));
MXYZ(3,1:length(csvfiles'))=MXYZ_l(3,1:length(csvfiles'));
MXYZ(4,1:length(csvfiles'))=MXYZ_l(4,1:length(csvfiles'));
MXYZ(1,length(csvfiles')+1:2*length(csvfiles'))=MXYZ_r(1,1:length(csvfiles'));
MXYZ(2,length(csvfiles')+1:2*length(csvfiles'))=MXYZ_r(2,1:length(csvfiles'));
MXYZ(3,length(csvfiles')+1:2*length(csvfiles'))=MXYZ_r(3,1:length(csvfiles'));
MXYZ(4,length(csvfiles')+1:2*length(csvfiles'))=MXYZ_r(4,1:length(csvfiles'));
xlswrite('results/YEAR-Hands(xyz).xls',MXYZ');
elseif choice==7;
xlswrite('results/YEAR-Torso(xyz).xls',TORSO');
elseif choice==8;
xlswrite('results/YEAR-Head(xyz).xls',HEAD');
else;
error('Error!! Could not find any data');
end;
%%;
toc %ends timer;
close all force;
```