CLASSIFYING VARUS THRUST VIA WEARABLE & OPTICAL MOTION CAPTURE

CLASSIFYING VISUALLY DEFINED VARUS THRUST IN KNEE OSTEOARTHRITIS USING WEARABLE INERTIAL SENSORS AND MARKERLESS MOTION ANALYSIS

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TITLE: Classifying Visually Defined Varus Thrust in Knee Osteoarthritis Using Wearable Inertial Sensors and Markerless Motion Analysis

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LAY ABSTRACT

This study explored varus thrust, a sudden and abnormal outward knee movement observed during walking, particularly seen in people with knee osteoarthritis (OA). Knee OA is a painful chronic condition affecting over 300 million people globally. Traditionally, varus thrust is identified visually by clinicians, who assess whether varus thrust is visibly present or not. However, this method is subjective and inconsistent. To improve varus thrust assessment accuracy and consistency, this study used wearable sensors and advanced motion capture camera systems to objectively measure knee joint movement during walking in knee OA patients. The results showed that varus thrust could be accurately identified by the wearable sensors measuring the outward acceleration of the upper shinbone area, directly below the knee joint. These findings are promising and demonstrate the utility of wearable sensor-based measurement of varus thrust. Further research is needed to validate these results and explore their broader application.

ABSTRACT

Varus thrust (VT) is a gait phenomenon seen in people with knee osteoarthritis (OA) that involves a sudden lateral movement of the knee joint, occurring within the first portion of the stance phase of the gait cycle. It is associated with improper joint loading and disease progression. Currently, visual assessment is the standard method for identifying VT but is subjective and prone to variability. The aim of this study was to explore and evaluate technological methods for assessing VT presence, using objective measurement tools. Visual VT assessment served as the reference standard, while markerless optical motion capture and wearable inertial sensor data were collected concurrently. Visual VT presence was initially assessed using a discrete scale that was based on the number of times it was observed, across multiple walking passes made by each participant. Motion capture data collected from 10 synchronized cameras were used to calculate frontal plane joint excursion (degrees), which was the variable of interest from the optical motion capture system. Participants also wore an inertial sensor on their upper tibia during their walking trials, and from these devices, information on their lateral tibial acceleration (m/s^2) and their peak frontal plane tibial angular velocity (degrees/s) were obtained. The results showed that peak lateral acceleration, measured by wearable sensors, had good discriminatory power in identifying visual VT presence, particularly in more visually apparent cases. These findings represent an important first step toward establishing objective, sensor-based methods for VT detection in clinical and research settings. Further research is needed to validate the outcomes, improve measurement accuracy in moderate presentations, and assess reliability across diverse clinical populations.

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LIST OF ALL ABBREVIATIONS

ANOVA – Analysis of Variance
AUC – Area Under the Curve
EKAM – External Knee Adduction Moment
FTA – Femorotibial angle
GRF – Ground reaction forces
IQR – Interquartile Range
IMU – Inertial Measurement Unit
KAM – Knee Adduction Moment
OA– Osteoarthritis
OARSI – Osteoarthritis Research Society International
PRP – Platelet-rich plasms
REDCAP – Research and Electronic Data Capture
RMSE – Root mean squared error
ROC – Receiver Operator Characteristic
TA – Thrust Acceleration
TKA – Total Knee Arthroplasty
VT – Varus Thrust
WOMAC – Western Ontario and McMaster Universities Osteoarthritis Index

CHAPTER 1: INTRODUCTION

Osteoarthritis (OA) is a prevalent chronic joint disease that significantly impacts the quality of life of millions worldwide and imposes a substantial burden on healthcare systems (Giorgino *et al.*, 2023). Affecting approximately 300 million individuals globally, people with OA incur medical expenses and lost earnings totaling over $300 billion annually (Abramoff *et al.*, 2020). This progressive degenerative disorder is characterized primarily by the degradation or destruction of articular cartilage in joints, along with changes in surrounding tissues. Degradation of this cartilage often leads to pain, inflammation, impaired mobility, and reduced joint functionality, collectively diminishing overall quality of life.

Among all joints susceptible to OA, the knee is the most common site of incidence (Turkiewicz *et al.*, 2015), with a global incidence rate of 203 per 10,000 persons per year (Cui *et al.*, 2020). The pathology and pathogenesis of knee OA are continuously evolving fields of study. Research has identified that abnormal gait kinematics and aberrant mechanical loading at the knee may contribute to the disease (Tsukamoto *et al.*, 2023) and targeting these factors may help avoid the traditional end-stage solution of an invasive total knee arthroplasty (TKA; Primorac *et al.*, 2020). However, collecting and quantifying information about knee joint loading and dynamic knee joint function in patients living with knee OA is generally impractical in a clinical setting. Acquiring this information requires comprehensive gait analysis and in-ground force plate data, which are not only expensive and time-consuming processes, but also require the expertise of skilled assessors and technicians. For example, researchers often rely on measures such as external knee adduction moment (KAM) to assess dynamic knee joint function by estimating the force distributions around the frontal plane of the knee. Studies have shown that KAM is associated with the progression and prognosis of medial knee OA, making it a valuable variable of interest

(Andriacchi *et al.*, 2009; Hurwitz *et al.*, 2002; Iwama *et al.*, 2021; Miyazaki *et al.*, 2002). Despite its utility and promising potential, using KAM as a proxy for loading in knee OA still remains challenging given the need for expensive and sometimes inaccessible equipment, as well as a large, dedicated space for data collections (Iwama *et al.*, 2021).

Varus thrust (VT) has emerged as another surrogate measure for evaluating dynamic knee joint loading, particularly in the medial compartment. VT is an abnormal motion of the knee joint, often present during the gait cycle of medial knee OA patients (Tsurumiya *et al.*, 2021; Tsukamoto *et al.*, 2021). This phenomenon is characterized by an abrupt lateral movement of the knee joint upon acceptance of the total body weight during the beginning of the single stance phase of walking (Tsurumiya *et al.*, 2021). VT is an acute, yet significant representation of dynamic knee misalignment and instability that has been associated with pain (Lo *et al.*, 2012; Fukutani *et al.*, 2016), medial compartment loading (Iwama *et al.*, 2021), and disease progression (Chang *et al.*, 2004; Sharma *et al.*, 2017; Wink *et al.*, 2017). Unfortunately, despite its potential significance and straightforward theoretical definition, there has been a lack of definitive consensus regarding how best to quantify VT.

A wide variety of gait analysis techniques have been employed to assess VT, yet no single technique or technical definition has gained widespread acceptance. One such measurement method is visual assessment, which typically requires little to no equipment, and involves clinicians or researchers observing the gait of adults with knee OA to rate the presence of VT based on outward appearance. The simplicity and practicality of this technique likely contributes to its frequent use in research exploring the relationship between modifications to VT and the slowing of knee OA disease progression (Chang *et al.*, 2004; Sharma *et al.*, 2017; Wink *et al.*, 2017). However, this assessment method has notable limitations, including reliance on a simplified rating system that is inherently subjective (Iijima *et al.*, 2017; Chang *et al.*, 2013). More objective techniques to measure VT incorporate the use of three-dimensional motion capture technology (*e.g.*, frontal plane knee excursion; Espinosa *et al.* 2020; Hall *et al.*, 2018) or wearable inertial sensors to assess lateral acceleration peaks (Ishii *et al.*, 2023) or the rate of frontal plane angular rotation (Costello *et al.*, 2020).

Despite advances in objective assessment methods, it remains unclear how well these quantitative measures of varus motion correspond to the clinically grounded concept of visually defined VT. While inertial sensor-derived metrics have shown associations with pain and disease severity, their relationship to visually observed VT is not well established. Additionally, limited and inconsistent research has compared VT identification across different modalities (Chang *et al.*, 2013; Murro *et al.*, 2025; Tsukamoto *et al.*, 2021) including visual assessment, motion capture, and wearable sensors. Therefore, the purpose of this study was to evaluate the extent to which peak tibial lateral acceleration and peak tibial frontal plane angular velocity derived from singular wearable sensors, as well as frontal plane knee joint angular excursion from markerless motion capture, align with visually assessed VT in the gait of older adults with knee OA. By comparing these modalities, this work aims to clarify how different assessment techniques relate to each other and to inform the development of accessible, reliable, and quantitative tools for identifying VT in clinical and research settings.

CHAPTER 2: LITERATURE REVIEW

Understanding knee joint kinematics, particularly medial knee joint loading, is an essential step towards better understanding and treating knee OA. To further explore the foundations behind this idea, a brief, yet thorough background on knee OA, its pathophysiology, treatment, and rehabilitative options, will be discussed. Then, previous and current research on knee osteoarthritic gait patterns and important gait variables, like KAM and VT, will be explored. Following that, an examination will be conducted of key studies in the field of VT assessment, highlighting the three main methods, along with their benefits and disadvantages. Finally, this literature review will be completed with a brief summary synthesizing all of the presented information along with connections to the proposed study.

2.1 – Brief Background on Knee Osteoarthritis and Treatment Methods

According to a review conducted by Lespasio *et al.* in 2017, OA has been established as one of the leading causes of disabilities the world over, with a projected increase in incidence as the population ages and the obesity epidemic worsens. Approximately 10% of men and 13% of women over the age of 60 suffer from knee OA, with women and Black individuals having an increased likelihood of developing the disease (Primorac *et al.*, 2020). With an increase in prevalence of approximately 32.7% from 2005 to 2015, and an approximate annual healthcare cost of $89.1 billion (Primorac *et al.*, 2020), the toll that knee OA has and will seemingly continue to have on society is immense and warrants urgent preventative measures.

The origins and pathogenesis of knee OA and OA, in general, are concepts that have long been shrouded in mystery. Lespasio *et al.*'s 2017 article reviewed over 49 studies investigating knee OA, and the conclusion was made that while the disease pathophysiology is insufficiently understood, the origin behind knee OA is multifactorial. OA is currently understood to involve articular damage or degeneration, bony osteophyte formation, and the stiffening of the bone beneath the cartilage, within joints (Lespasio *et al.*, 2017). The diagram in Figure 1, created by Anika Therapeutics, Inc. (2025), illustrates the physical characteristics of knee OA compared to a healthy knee joint, including the growth of osteophytes (bone spurs) and the degeneration of articular cartilage and other cartilaginous aspects of the knee joint, like the meniscus.

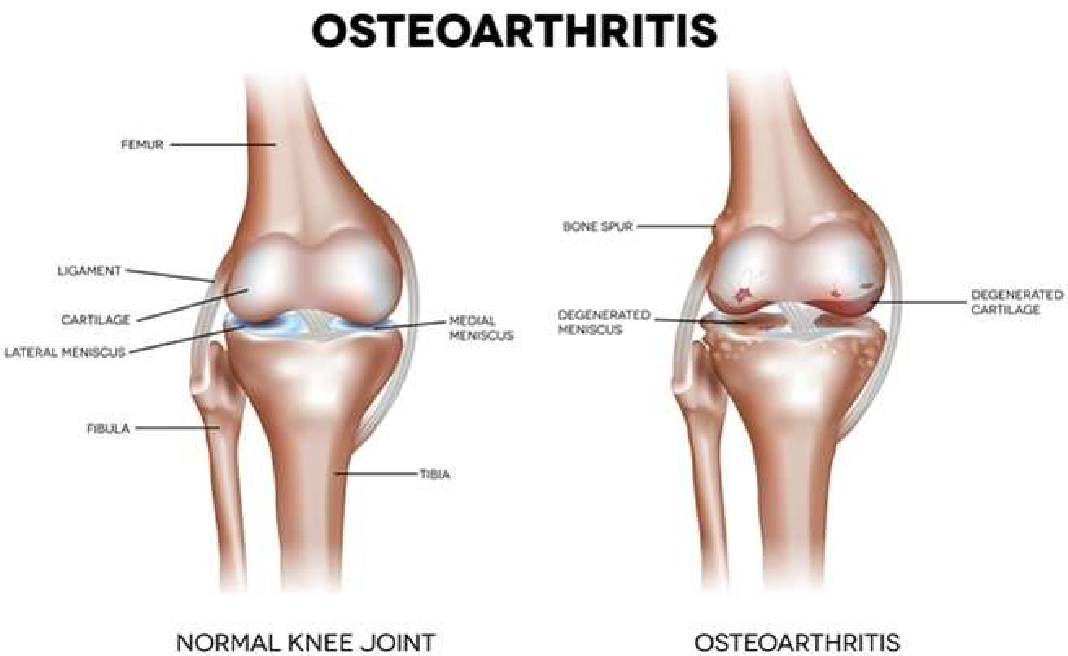

Figure 1: An illustration depicting the physiological symptoms of knee OA in comparison with a healthy knee joint (Anika Therapeutics, Inc., 2025)

These physiological changes then result in the symptomatic effects that lead patients to seek out their eventual diagnoses, such as constant or intermittent pain, decreased range of motion, muscle weakness, grinding or popping joints, swelling, locking, or giving way of the knee, difficulty walking or climbing stairs, and an overall decreased quality of life (Lespasio *et al.*, 2017).

Though the characteristics and clinical symptoms of knee OA are clear, its origins are only speculated to be rooted in abstract concepts such as age, family history, diabetes, lower limb alignment, with supplemental risk factors like genetic mutations and being overweight (Lespasio *et al.*, 2017). However, no specific factors have been identified to specifically cause the disease, which makes treatment and prevention plan development more challenging.

Another aspect of knee OA pathology that is often highlighted in literature is the nature of its progression as well as the varying types of end-stage treatment options. Knee OA progression is typically tracked using a variety of rating systems that assess the state or change from baseline of the patients' disease symptoms. Particularly, knee joint space narrowing is a common and easily observable metric that can be obtained through the use of radiographic imaging technology. The Osteoarthritis Research Society International (OARSI) atlas grades joint space narrowing based on whether there is none, possible narrowing, definite narrowing, or severe narrowing (Chang *et al.*, 2004). Another one of the more widely used rating scales is the Kellgren-Lawrence grading scale which categorizes knee OA patients on a scale of 0 to 4, based on factors like knee joint space narrowing, osteophyte formation and bone sclerosis (Chang *et al.*, 2004; Sharma *et al.*, 2017). Knee OA progression can also be tracked using assessments of physical functionality. The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) physical function subscale is a validated, self-report instrument, ranging from 0 to 68, with higher scores indicating worse or decreasing function (Chang *et al.*, 2004). Increase in severity in accordance with these scales as well as general increases in symptom severity are what allow physicians and researchers to determine how patients' knee OA is progressing in order to inform treatment or rehabilitative options, as well as to determine whether they are in need of end-stage care.

Rehabilitative or physical therapy is often the first option explored in the prevention of knee OA disease progression (Jahn *et al.*, 2024). Techniques involve heat and cold therapy, ultrasound therapy, electrical stimulation therapy, massages, acupuncture, or exercises that progressively work to reduce pain, increase joint mobility, muscle strength, blood flow, and/or range of motion (Jahn *et al.*, 2024). More recently, intra-articular injections have been showing promise as a treatment option for younger patients or patients with less disease progression (Lespasio *et al.*, 2017). Corticosteroid, hyaluronic acid, and platelet-rich plasma (PRP) are a few examples of the types of injections that have been developed and employed to try to target the physiological and structural aspects of the knee joint's components, and slow disease progression (Primorac *et al.*, 2020). Despite the increase in use of these injections to treat pain and other knee OA symptoms, a distinct lack of robust high evidence determining their efficacy has been found, establishing the need for further high-quality research (Bennell *et al.*, 2021).

Once the disease has progressed past the point where physical and other alternative forms of rehabilitative therapy can be of use, end-stage options have to be explored. Total knee arthroplasty or TKA has been the main form of treatment for knee OA since 1968 (Primorac *et al.*, 2020). A TKA involves replacing or resurfacing all aspects of the knee joint with prosthetic material to increase functionality and quality of life of knee OA patients. Specifically, metal and plastic implants are designed to mimic the damaged articulating surfaces of the ends of the femur and tibia and increase the diminished joint space within the knee. Other surgical variations like partial knee arthroplasties (PKA) have since been developed for cases where damage is only seen in one side or section of the knee, thus requiring lesser prostheses. The x-ray images in Figure 2 illustrate post-operative knee joints after undergoing TKA and PKA (Haffar *et al*., 2022).

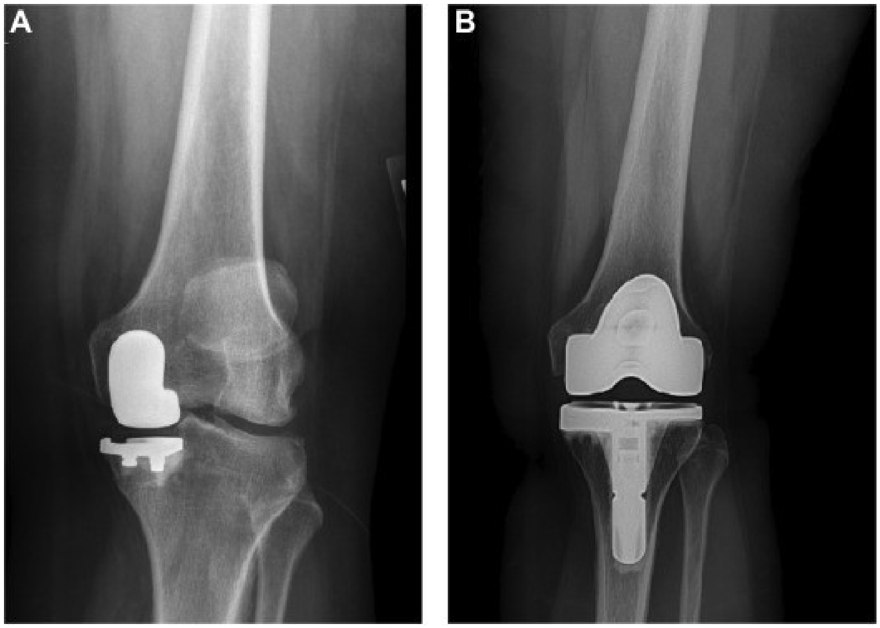

Figure 2: Post-operative x-ray imaging of two knee joints that have undergone partial (left) and total (right) knee arthroplasties. The prosthetic material resurfacing the articulating aspect of the joint is highlighted in white.

Note. From *Staged bicompartmental knee arthroplasty has greater functional improvement, but equivalent midterm survivorship, as revision TKA for progressive osteoarthritis after partial knee arthroplasty*, by Haffar, A., *et al.*, 2022, *The Journal of Arthroplasty, 37*(7), p. 1262. https://doi.org/10.1016/j.arth.2022.02.084. Copyright 2022 by Elsevier. Fair use.

A high tibial osteotomy is another procedure often considered when OA is confined to a single knee compartment. Its goal is to offload or redistribute joint forces away from the affected area (Lespasio *et al.*, 2017), with the hope of delaying disease progression and the worsening of both internal joint damage and external symptoms.

Overall, while some of these treatment options have proven effective in reducing knee OA symptoms and slowing disease progression, their expensive, invasive, and inherently high-risk nature makes them less feasible and practical for the growing population of older adults suffering from knee OA. Thus, research must focus on seeking to prevent end-stage progression through external malleable, non-invasive methods, which can be found and observed through gait analysis.

2.2 – Knee Joint and Knee Osteoarthritis Gait Characteristics

The knee joint is comprised of three compartments: the medial tibiofemoral compartment (connects medial tibia to the medial femur), the lateral tibiofemoral compartment (connects the lateral tibia to the lateral femur), and the patellofemoral joint (connects the anterior kneecap to the femur). OA can develop within each compartment or within multiple joint compartments, however, the medial compartment is the most common location (Tsukamoto *et al.*, 2023). This is likely related to a greater load placed on the medial compartment in some individuals. Knee joint loading thus becomes a concept of great interest when assessing the pathophysiology of knee OA.

When focusing on knee joint loading in relation to knee OA, it is most common to use proxy or surrogate measures in place of knee joint loading itself. It is generally not feasible, efficient, or practical to measure dynamic forces within a joint directly, so substitute values, like external knee adduction moment (KAM or EKAM) and VT, are used.

2.2.1 - Knee Joint Parameters: Knee Adduction Moment

External knee adduction moment is the moment of force generated around the frontal plane of the knee joint, while walking. This moment is generated by the ground reaction forces (GRF) that pass through the medial knee joint during walking, and thus, EKAM is seen as a reflection of the compressive forces applied to the medial compartment of the knee (Kutzner *et al.*, 2013). The image below illustrates EKAM as it is derived from the GRF, and the moment arm drawn perpendicularly from the knee joint center to the line of the GRF (Figure 3). Additionally, another characteristic of KAM is its dual peak manifestation, during ambulation. Over the course of the gait cycle, knee adduction moment values are visualized as two distinct peaks, one during early stance and one during late stance (Figure 4). The stance phase of gait refers to the period of time when one foot is in contact with the ground and bearing weight, or from a single foot's heel-strike to its toe-off (Laribi *et al.*, 2020).

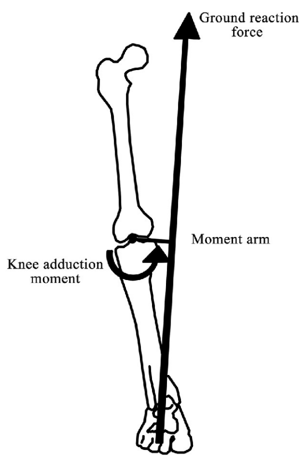

Figure 3: A depiction of Knee Adduction Moment and the biomechanical components it is derived from.
Note: From *Effect of exercise and gait retraining on knee adduction moment in people with knee osteoarthritis*, by Khalaj, N., *et al.*, 2014, *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine*, 228. https://doi.org/10.1177/0954411914521155. Copyright 2014 by the authors. Fair use.

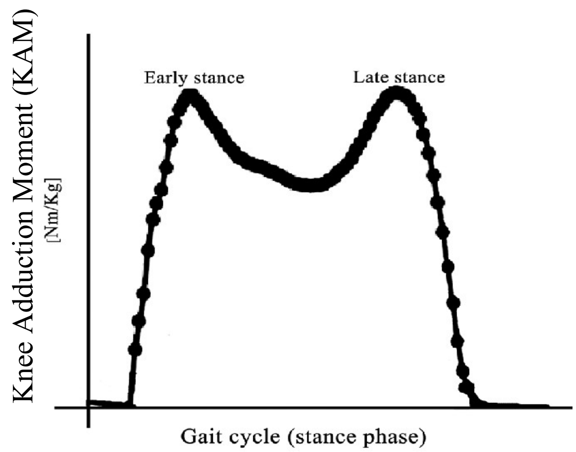

Figure 4: Graph depicting the progression of KAM throughout the stance phase of the gait cycle.
Note: From *Effect of exercise and gait retraining on knee adduction moment in people with knee osteoarthritis*, by Khalaj, N., *et al.*, 2014, *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine*, 228. https://doi.org/10.1177/0954411914521155. Copyright 2014 by the authors. Fair use.

Numerous studies have used knee adduction moment to measure medial knee joint loading when assessing the effectiveness of knee OA treatment options, operating under the notion that a decreased knee adduction moment indicates decreased knee joint loading. Thus, in theory, any therapies or gait modifications that reduce knee adduction moment should contribute to the slowing of knee OA disease progression. Some examples of KAM-reducing modifications that are associated with slowed knee OA disease progression are barefoot walking, walking with toes pointed outward, walking with a shorter stride, and walking with a medial thrust gait (Khalaj *et al.*, 2014). The major drawback with studying and focusing on KAM for knee OA research, however, is its accessibility. In order to collect KAM data, researchers would need to have access to 3D motion analysis systems, to obtain spatial positioning data via markers, and force plates, to obtain the ground reaction force data (Mahmoudian *et al.*, 2016). While this full setup would be ideal for collecting robust KAM data, this equipment is expensive, may be hard to acquire, and would likely be impractical to incorporate into a larger-scale clinical setting where factors like time-constraints and location must be prioritized. Additionally, prior research has shown that attempts to reduce KAM via gait retraining and gait modifications have not been as efficacious as needed, such as interventions reducing late stance KAM peaks while simultaneously increasing early stance KAM peaks (Simic *et al.,* 2011). Tradeoffs like these and the other aforementioned limitations are what bring researchers to seek out other, more easily acquirable surrogate measures for medial knee joint loading, like VT.

2.2.2 – Knee Joint Parameters: Varus Thrust

According to a 2016 article by Mahmoudian *et al.*, "varus thrust is a dynamic malalignment of the knee that has been defined as an abrupt increase of the knee varus angle when the leg is bearing weight, with a decrease during the non-weight-bearing phase of ambulation (swing phase)." In short, it is a brief lateral/outward thrust of the knee that is seen while weight is applied, during walking, and subsequently goes away once weight is removed. VT is an abnormal gait pattern typically seen in patients with medial knee OA (Misu *et al.*, 2023). The image below (Iijima *et al.*, 2017) shows a comparison of a stride where VT is visibly present during the stance phase, and one where it is not.

Figure 5: An image showing the visible difference between a person walking with varus thrust and a person walking without varus thrust. The white circle represents the center of the knee joint while the white lines extending from it depict the positions of the thigh and the lower leg in relation to each other, creating the varus angle at the knee.

Note: From *Association of varus thrust with prevalent patellofemoral osteoarthritis: A cross-sectional study*, by Iijima, H., *et al.*, 2017, *Gait & Posture, 58*, 394–400. https://doi.org/10.1016/j.gaitpost.2017.08.033. Copyright 2017 by Elsevier. Fair use.

VT has been shown to have a strong relationship with knee adduction moment and knee OA disease progression (Chang *et al.*, 2004; Kuroyanagi *et al.*, 2010), making it an ideal variable to observe when seeking an alternative to KAM. Specifically, the presence of VT is said to be associated with a higher EKAM, which is affiliated with higher medial knee joint loads that subsequently leads to disease progression (Mahmoudian *et al.*, 2016). Furthermore, research has deduced that the nature of a varus thrust occurrence may be attributed to failed efforts of the lateral soft tissues and adjacent muscle, to effectively counteract the KAM, and stabilize the knee joint (Chang *et al.*, 2004). Presence of VT has also specifically been linked with increased pain and joint stiffness in those with medial knee OA (Fukutani *et al.*, 2016), and increased chances of patellofemoral OA in people who already have medial knee OA (Iijima *et al.*, 2017). Studies have proposed that VT is linked with isokinetic strength deficits of the lower body (Espinosa *et al.*, 2020) and increased incidence of bone marrow lesions and worsening medial cartilage loss (Wink *et al.*, 2017), all further cementing the importance of studying VT in knee OA patients.

2.3 – Gait Analysis and Varus Thrust

VT as a phenomenon is newly emerging in the research world and as a result, research methods for obtaining data pertaining to it are primarily exploratory and unstandardized in nature. Currently, the three most common VT data collection methods that have been employed are visual assessments, camera-based motion capture, and wearable sensor-based assessments. Based on current research, each collection method has predominantly been employed independently, which makes them easier to assess when analyzing their advantages and disadvantages.

2.3.1 – Visual Assessments of Varus Thrust

The most commonly used method of assessment of VT is through visual or observational methods. This method involves observation of the knee by clinicians or researchers, during weight-bearing activities, to identify the presence and severity of VT. The knee posture is then classified using a qualitative or semi-quantitative rating scale of the researchers' choosing, based on the physical definition of VT. For example, a study by Sharma *et al.* conducted in 2017 relied on 2-3 examiners who underwent a didactic session as well as practice evaluations on volunteers with known thrust statuses. Approximately 3,000 knees from this study were then classified as either having VT present or not. Like many studies in this field, Sharma *et al.* based much of their VT measurement methodology on Chang *et al.*'s 2004 article examining the relationship between VT and knee OA disease progression. While Sharma *et al.* aimed to expand the scope of the initial Chang *et al.* study by increasing the number of examiners and sites used to assess VT, the data extracted was still rudimentary in nature, as a binary establishment of whether VT was visible. These studies are a testament to the major benefit of visual assessment methods, being that they were able to maintain nearly identical methodologies due to their simplicity. Both studies blinded their examiners, standardized participant clothing and standardized instructions given to the participants, in order to reduce sources of potential bias (Chang *et al.*, 2004; Sharma *et al.*, 2017).

In an effort to add more detail to this measurement technique, tools like Likert scales have been incorporated into studies aiming to determine VT more decisively, while still using visual assessment. Likert scales in this field allow researchers to obtain semi-quantitative data by outlining qualitative parameters on a more discrete scale. For example, studies conducted by Iijima *et al.* in 2017 and 2019 made use of a Likert scale to establish the presence of VT by determining if VT was 'definitely present,' 'possibly present,' or 'definitely absent'. The VT measurement was thus made semi-quantitative by introducing a range of classification options. However, the effects of this technique were almost immediately attenuated when the data was later consolidated into two groups, where those with 'definitely present' VT were categorized into the "with definite varus thrust" group and all others were classified into the "without definite varus thrust" group. Understandably, the researchers' goal was to ensure that only participants with obvious VT were considered to avoid false positive categorizations, but in doing so, they have also reduced the specificity created by the rating system, which may have influenced their outcomes. In fact, in the 2017 study by Iijima *et al.*, they stated that a specific definition of VT would alter the results of their correlational study, with the 'possibly present' category leading to a weaker relationship between their two variables of interest, VT and patellofemoral OA.

Other studies, such as a 2013 study conducted by Chang *et al.*, also made use of a Likert scale to assess VT. This study was unique because it incorporated further elements of subjectivity through the use of a confidence scale. The difference is subtle but while the Iijima studies used the definite presence or lack of obvious VT, the Chang *et al.* study added the confidence level of the assessors. Assessors were tasked to first identify whether varus or valgus thrust was present and then follow up with a rating level of 'very confident', 'somewhat confident', 'not very confident', or 'not at all confident', regarding their decision. The study cites this subjective measure as a limitation but notes that upon conducting a sensitivity analysis, that included both the 'very confident' and somewhat confident' categories in their statistical analysis, they found similar results to what they found when they only included the 'very confident' ratings. While this consistency was largely due to the strength of the relationship between the variables being compared, one can also attribute this lack of change to the efficacy of the Likert scale, when contextualized with additional parameters.

In essence, the literature and studies conducted relying partially or solely on visual assessment of VT demonstrate both its ease of use and implementation, and its need for fortification with the addition of external parameters. Despite the valuable progress that assessment via visual VT has been able to contribute to the field of knee OA, particularly regarding understanding the disease's progression, this methodology still lacks the nuance and objectivity necessary to generalize the studies' findings and support repeatable, reliable techniques and outcomes. More concrete and quantifiable data are inevitably needed to explore a wider variety of variables and relationships such as VT severity and how this may impact knee OA characteristics.

2.3.2 - Camera-based motion capture of Varus Thrust

Continuous technological advancements and increasing efforts to quantify VT have led to the implementation of camera-based motion capture technology in this field. This technology, also called optical motion capture technology, involves the use of a multi-camera set up that is configured to capture multiple fields of view of a subject's gait. These multiple perspectives can later be observed and analyzed directly or processed using external processing software. The two main types of optical systems are marker-based, like the Vicon (Vicon Motion Systems Ltd., Yarnton, Oxfordshire, UK) and Optitrack (NaturalPoint, Inc., Corvallis, OR, USA) systems, and markerless, like the Ariel Performance Analysis (Ariel Dynamics, Inc., San Diego, CA, USA) and Theia (Theia Markerless, Kingston, ON, Canada) systems.

A major study in this field that used marker-based motion capture was conducted in 2016 by Mahmoudian *et al.*, where researchers evaluated the presence and severity of VT and compared it between women with early-stage medial knee OA and healthy controls. This study relied on a passive marker-based optical system, where the markers they used were coated in retroreflective material, designed to reflect light generated from near the lenses of the cameras being used to record motion (Prakash *et al.*, 2015). The sensitivity of the cameras used in conjunction with passive markers is also adjusted to only sample the light reflected from the markers and filter out reflections from the skin and other objects. Passive markers are often easier to implement as they do not require external power sources, are less invasive, and are more cost-efficient in comparison to the alternative marker-based method, which is using active markers. The authors of the 2016 Mahmoudian *et al.* study defined VT as "the difference between the knee adduction angle at heel strike and the first maximum knee adduction angle during the stance phase of gait". This operational definition based on the frontal plane range of motion at the knee had been derived from a 2004 study by Chang *et al.* and a 2012 study by Kuroyanagi *et al.* Based on this definition, participants were classified as having VT or not based on the median VT value for the study's sample population, which was 2.02 degrees (Mahmoudian *et al.*, 2016). In contrast, other studies, such as the Hall *et al.* (2018) study defined VT using peak values of varus angle (-1.4 degrees), frontal plane knee excursion (4.6 degrees) and angular varus velocity (54.3 degrees/s). Unfortunately, there has been little to no research in this field examining which variables and which VT-based interpretations are most valid for measuring VT, due to a lack of studies combining measurement methodologies. The Kuroyanagi *et al.* (2012) study and others with similar methods did, however, incorporate a force plate to determine ground reaction forces and obtain knee adduction moment (KAM) data, by projecting the knee moments onto the shank coordinate system. This study contributed to great advancements in the field of VT assessment by determining that those with early-stage medial knee OA had both a greater prevalence and magnitude of VT, as compared to their healthy counterparts. Despite the strong results and valuable contributions gained from the results of this study, a major limitation that they acknowledged was with their sample population being limited in size and restricted to only women, asserting the need for further research. The researchers also did not evaluate their operational definition of VT for validity or accuracy using any outside measure, reducing the strength of their methodology and further emphasizing the need to determine a standardized quantitative measure of VT. Finally, while marker-based motion capture systems have been acclaimed for their high accuracy, they tend to be costly, require a complex setup process, and marker application can be a time-consuming process subject to inconsistency or variability across testers (Das *et al.*, 2023).

Regarding the alternative marker-based method of optical motion capture, active marker-based systems use markers that are built to emit their own light at varying frequencies or signals, that can then be detected by motion capture cameras (Prakash *et al.*, 2015). Similar to the passive system, once the cameras have recorded the motion and the light or reflections of light generated from the corresponding markers, the motion capture processing software estimates the 3-dimensional position of the center of each marker based on the 2-dimensional view captured by the cameras used. Active markers have the added benefit of being less susceptible to reflections from unmarked objects, making it optimal for use outdoors or in settings where highly reflective materials cannot be removed or concealed. Despite its utility, active marker setups are less popular due to their affiliated higher costs, more complex setup and higher impact on a subject's movement (Prakash *et al.*, 2015), making passive marker systems the more accessible method.

Markerless motion capture systems are the more easily implementable alternative to traditional marker-based motion capture systems. Markerless systems rely on processing through machine-learning algorithms applied to recorded videos of human movement, to develop digital model estimates based on multiple synchronized camera perspectives of human motion. These models are then used to derive various variables of interest based on relative body positioning, as opposed to the fixed measurements obtainable through marker-based motion capture. Markerless motion capture systems have recently begun to be used in the field of varus thrust measurement in knee osteoarthritic populations, for their lower costs, portability, simpler setup process (Das *et al.*, 2023), non-invasive nature (Cabarkapa *et al.*, 2022), and similarity in measurement patterns to their marker-based counterparts (Fleisig *et al.*, 2021). Of the limited number of studies conducted using markerless motion capture in knee OA populations, a 2022 study by Ekanayake *et al.* made use of the DARI Motion markerless system to assess the relationship between patient reported outcome measures and office-based functional performance, in end-stage preoperative knee OA patients. While the study's results established that there was no strong correlation between the two concepts, the validity and viability of the markerless system to assess functional capacity was greatly emphasized. The feasibility and ease of implementation of markerless systems into fast-paced clinical environments were also cited as having major potential for the development of future clinical research and measurement methodologies.

A more recent study published in 2023 explored the validity of using markerless motion capture to analyze knee varus alignment by comparing it to traditional radiographic imaging techniques and marker-based motion capture (Todoriki *et al.*, 2023). The study specifically looked at the femorotibial angle (FTA), the angle formed between the femur and the tibia in the frontal plane, which they used to define varus alignment. While this study addressed many gaps, such as lack of research validating markerless motion capture in the measurement of FTA and limited research using the above methods on clinical populations, their focus was on static knee alignment. VT is a phenomenon detected during dynamic movement and while static alignment has also been linked to an increased risk of knee OA and its progression (Sharma *et al.*, 2001), dynamic knee alignment can provide a more holistic depiction of the knee's behaviours as well as potentially reveal habits or positions that may not be visible when stationary. Nevertheless, the study was able to assert that the collected markerless motion capture data was not only significantly related to the radiographic data, but also that the markerless method was able to adequately assess the severity of the varus misalignment. These positive results drive the need for more research validating markerless motion capture to analyze dynamic movements, while further highlighting the lack of standardized quantitative definition of dynamic knee alignment or VT.

2.3.3 - Wearable sensors to measure Varus Thrust

Inertial sensors, also known as Inertial Measurement Units (IMUs), are a low-cost, highly portable method of obtaining various gait variables (Das *et al.*, 2021). IMUs are typically composed of accelerometers, gyroscopes, and/or magnetometers, on which they rely to collect data on the velocity, acceleration, and orientation of human body segments. These sensors tend to be compact, with all their components assembled into a singular unit that can often fit into the palm of one's hand. These units can then be attached to the body using adhesives or straps.

IMU-sensor derived measures have been used to support the definition of VT using a variety of operational definitions, specific to their study. For example, a 2021 randomized control study was conducted by Tsurumiya *et al.* aiming to assess the gait of knee OA patients using IMUs to evaluate VT in relation to disease progression. The sensor system used required participants to be equipped with a sensor attached to the base of their trunk, two on the frontal aspect of each thigh and two on each shank, just below the knees. This five-sensor setup was attached using flexible bands and recorded data at a 100 Hz frequency, while participants completed a 10-metre free walking trial. For this study, VT was defined as the first peak values of the ML acceleration (*e.g.* 9 m/s^2; Tsurumiya *et al.*, 2021) and the frontal angular velocity at the shank (varus/valgus, *e.g.* 100 degrees/s; Tsurumiya *et al.*, 2021). While this study was able to obtain very compelling results detecting a strong relationship between VT and knee OA disease progression, they were limited by the fact that their IMUs' coordinate systems required the use of external alignment methods via optical motion capture systems to convert them to the local coordinate system of the body segments (Tsurumiya *et al.*, 2021).

In 2023, Tsukamoto *et al.* carried out a study aiming to classify VT based on IMU-mediated gait analysis in medial knee OA patients. Four sensors were used for this study's data acquisition and were placed on the anterior sides of the thigh and shank (Tsukamoto *et al.*, 2023). VT was classified into four categories based on the relative medial-lateral acceleration patterns between the shank and thigh segments, including medial thigh-medial shank, medial thigh-lateral shank, lateral thigh-medial shank, and lateral thigh-lateral shank. The figure below depicts a simplified version of how these patterns were detected and categorized.

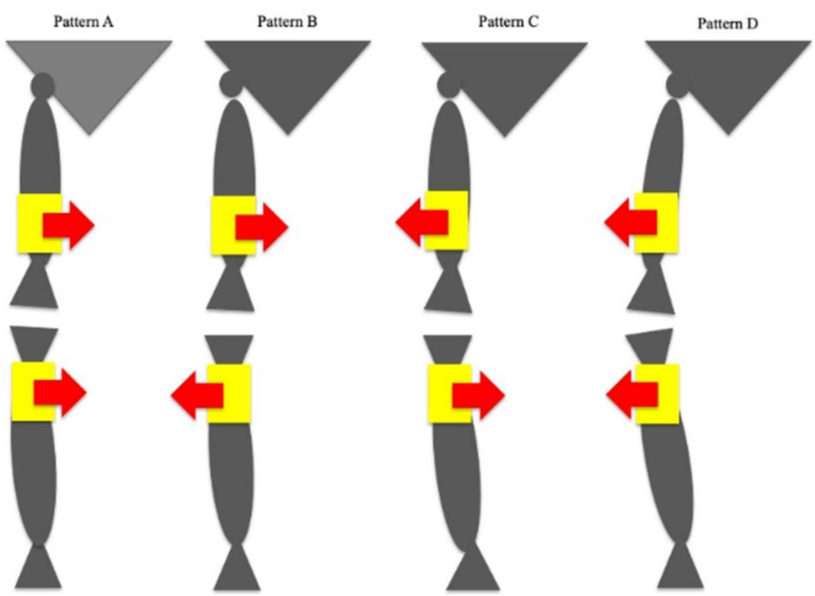

Figure 6: The IMU acceleration patterns between the thigh and shank segments that were used to classify varus thrust. Varus thrust was confirmed via the use of IMUs within knees demonstrating movement patterns C and D.

Note: From *A novel classification of coronal plane knee joint instability using nine-axis inertial measurement units in patients with medial knee osteoarthritis*, by Tsukamoto, H., *et al.*, 2023, *Sensors, 23*(5), Article 5. https://doi.org/10.3390/s23052797. Copyright 2023 by the authors. Licensed under CC BY 4.0.

Based on the data obtained from these wearable devices, VT was quantitatively defined as the maximum varus angle with the largest peak knee angular velocity during early stance phase (Tsukamoto *et al.*, 2023). Additionally, an expert orthopaedic surgeon was brought in for this study to assess the presence of clearly visible VT (Tsukamoto *et al.* 2023). One of this study's major findings was that a relationship was detectable between the shank and thigh acceleration patterns and the Kellgren-Lawrence medial knee OA stages. This is significant because VT is often not as easily detectable in early stages of medial knee OA, showing that there is merit to combining VT assessment methods. The study was also able to conclude that the use of IMUs was useful in detecting subtle knee joint motions, indicating joint instability, through measuring knee angular velocity, allowing for potential earlier detection of VT. The study did however cite numerous limitations such as a small sample size and larger estimation errors in the IMU data when compared against the 3D gait analysis due to skin motion and drift errors (Tsukamoto *et al.*, 2023). These errors are likely due to the older models of IMUs used for this study as the data was collected during 2017 and 2018, and the researchers acknowledge that IMU technology has advanced greatly since then.

Additionally, most of the studies primarily relying on wearable sensors for VT measurement utilized a multi-sensor setup with sensors that could cost anywhere between $100s and $1000s per unit. In an effort to minimize the number of sensors used, and indirectly minimize cost and setup time, researchers have turned to experimenting with single sensor setups. For example, Ogata *et al.* employed a single unidirectional accelerometer adhered to the tibial tubercle to measure VT in 1997. For this study, VT was defined as the first peak ML acceleration derived from the accelerographs generated by the accelerometers, and the strain gauges attached to the sole of each participant's foot, used to determine the time of heel strike. Like the Tsukamoto *et al.*

study, this study also made use of gait patterns with a lateral thrust pattern being defined as a lateral first acceleration peak followed by a medial second peak, and a medial thrust pattern having the opposite characteristics. The focus of this study was not specifically to quantify VT using a single sensor, but instead to assess changes in VT upon implementation of a wedged insole, shifting the emphasis away from the feasibility of using a single sensor.

A study conducted by Iwama *et al.* in 2021, however, did explore the feasibility of using a single IMU to collect data, but instead of VT, they observed KAM. Due to the strong relationship between KAM and VT that has already been established, studies exploring KAM are often referenced when observing VT, as they are commonly treated as substitute measures for each other. Six commercial IMUs (TSND151, ATR-Promotions) were attached to various body segments of participants and their signals were synchronized with a conventional marker-based 3D gait analysis system (Oqus, Qualisys). Additionally, two force plates were used during the 6-10 walking trials of 10-metre walking bouts. VT, referred to as thrust acceleration (TA) in this study, was defined as the peak-to-peak difference of the ML acceleration of the knee joint, immediately after heel strike (Iwama *et al.*, 2021). Across all the locations that the IMUs were placed, the ones affixed to the shanks and the pelvis demonstrated the strongest relationships between peak KAM and the TA ($R = 0.57$, $p < 0.001$, RMSE = 0.082 and $R = 0.52$, $p < 0.001$, RMSE = 0.079 respectively). These results established the feasibility and validity of estimating and monitoring KAM and VT using singular IMUs, while stating their need for more consistent measurement protocols and a wider demographic of participants (Iwama *et al.*, 2021).

2.4 – Synopsis of Literature Review

To conclude, while research in the field of VT and knee OA is still newly emerging, there is a reasonable foundation upon which one can aim to more clearly define VT. Research using visual assessment methods has paved the way in the field and established VT as a valuable variable of interest, despite the subjectivity and inconsistency of this methodology. Camera-based motion capture assessments of VT have not only opened doors to quantify a previously qualitative variable, but have also introduced more reproducible and accurate, albeit costly, results. Finally, wearable sensor-based assessment of VT has emerged as a portable, user-friendly method of assessment, requiring further research with larger sample sizes to strengthen its basis. Evidently, most of the research in this field has focused on singular methods of assessment of VT, making it difficult to discern a clear objective and quantitative definition. Some studies have combined 2 of the 3 main methods, such as Tsukamoto *et al.*, 2021 (multi-sensor joint angle assessment with visual assessment) and Hunt *et al.*, 2011 (camera-based and visual assessment), but none have tried to combine all three methods with the primary aim of defining and regulating the elusive concept of VT.

CHAPTER 3: THESIS RESEARCH QUESTIONS AND HYPOTHESES

Aim and Research Questions

The aim of this project was to evaluate the ability of wearable inertial sensors and an optical motion capture system to identify patterns of visually confirmed VT in gait. In-clinic gait data collected from the Fracture and Orthopaedics Outpatient Clinic at St Joseph's Hospital were analyzed to address the following research questions:

1) Can visually defined VT be identified using peak lateral tibial acceleration or peak frontal plane tibial angular velocity during the stance phase of gait, as measured by wearable inertial sensors?
2) Can visually defined VT be identified using frontal plane knee joint angular excursion during the stance phase of gait, as measured by an optical motion capture system?

Hypotheses and Impact

It was hypothesized that visually defined VT would be accurately identified (Area Under the Curve [AUC] of receiver operating characteristic curves > 0.8) by all modalities: peak lateral tibial acceleration, peak frontal plane tibial angular velocity, and frontal plane knee joint angular excursion.

This research seeks to better understand the quantification of VT in older adults with knee OA and to validate the accessible measurement approaches using either technology. A more precise and objective understanding of VT has the potential to enhance clinical assessment and monitoring, support targeted interventions, and inform future research focused on mitigating disease progression and improving functional outcomes in individuals with knee OA.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 – Participants

Forty-five older adult participants (17 males, 28 females; mean age = 65 ± 7.5 years) with advanced knee OA, who were seeking total or partial knee arthroplasty, were recruited from a larger gait study conducted at the St Joseph's Hospital Fracture and Orthopaedics Outpatient Clinic. Participants for this study were assessed for eligibility after completing their pre-operative consultation meeting with their surgeon, 1-2 weeks prior to surgery. The inclusion criteria required participants to have a knee OA diagnosis and the ability to ambulate without any walking aids. Exclusion criteria for this study were defined as having had any other knee replacement surgeries in the past, which was determined using the screening questionnaire, and/or being unable to provide informed consent. The study protocol was reviewed and approved by the Hamilton Integrated Research Ethics Board (HIREB) in Hamilton, Ontario (ID 16236). Prior to participation, each volunteer provided written informed consent and was free to withdraw at any time without penalty.

4.2 – Equipment

4.2.1 – Data Collection Environment

Data collection sessions were carried out on the third floor of the Juravinski Innovation Tower in the Orthopaedic Research hallway. This hallway is located three floors above the Fracture and Orthopaedics Outpatient Clinic on Floor 0, which is where participants were recruited from.

4.2.2 – Optical Motion Capture System

The Theia Markerless Motion Capture System (Theia Markerless, Kingston, ON, Canada) was used to collect data on lower limb segment orientation and positioning. This system relied on a 10-camera setup (Sony Cyber-shot DSC-RX0 II digital cameras) that had been pre-installed in key locations along the research hallway. The cameras have been programmed to record video at a rate of 60 Hz. Additionally, a 7.6-metre floor decal has been installed within the data collection area to allow for standardization of the walking path, as well as calibration of the Theia system.

4.2.3 – Wearable Sensors

Each participant was equipped with a pair of Axivity AX6 (Axivity Ltd., Newcastle upon Tyne, UK) inertial measurement units. The inertial sensors were adhered to the medial and proximal aspects of the shanks of the participants, with one below each knee, using waterproof adhesive tape. The location of the sensors was landmarked by locating the tibial tuberosity, then moving medially to the flat part of the tibia, where the sensors were then placed. Each sensor records linear acceleration and angular velocity data at a rate of 100 Hz across an ±8 g and ±1000 degrees/s dynamic range, respectively.

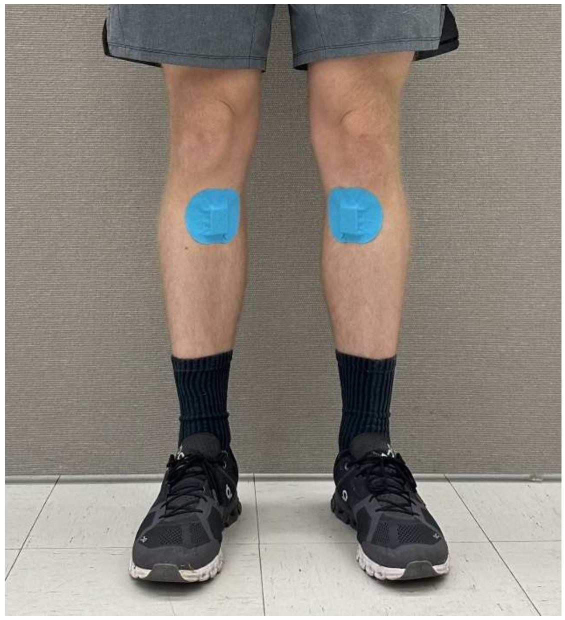

Figure 7: An image demonstrating the placement of the Axivity AX6 inertial measurement units, for this study.

4.3 – Data Collection Protocol

For each participant, data was collected during one in-clinic session lasting approximately 15 minutes in duration. During this session, participants provided informed consent before completing a survey administered by a research assistant, documenting each participant's demographic information, medical history, surgical expectations, and mental health history. The survey was designed and administered through the Research Electronic Data Capture (REDCap) software. After completion of the survey data, movement collections were conducted using both the Theia Markerless Motion Capture System and wearable Axivity AX6 inertial sensors, simultaneously. This study was a part of a larger study involving multiple functional tests (*e.g.*, balance, walking, sit-to-stand, stairs) and free-living (*e.g.*, 7-day out-of-lab) sensor data. For the current study's research goals, only in-clinic data for the preferred walking task was assessed. Specifically, participants were asked to walk at a comfortable, self-selected pace back and forth across the 7.6-metre decal for 60 seconds, or until they completed six passes, whichever occurred first, with all sensor systems recording simultaneously. They were also instructed to begin their turns only after stepping off the floor decal, ensuring that all turns occurred outside the view of the cameras and did not interfere with data collection during the walking bouts.

4.4 – Data Processing

While quantitative walking data was being derived from the two systems (Theia and Axivity), there were three levels of data to analyze and process further (Figure 8).

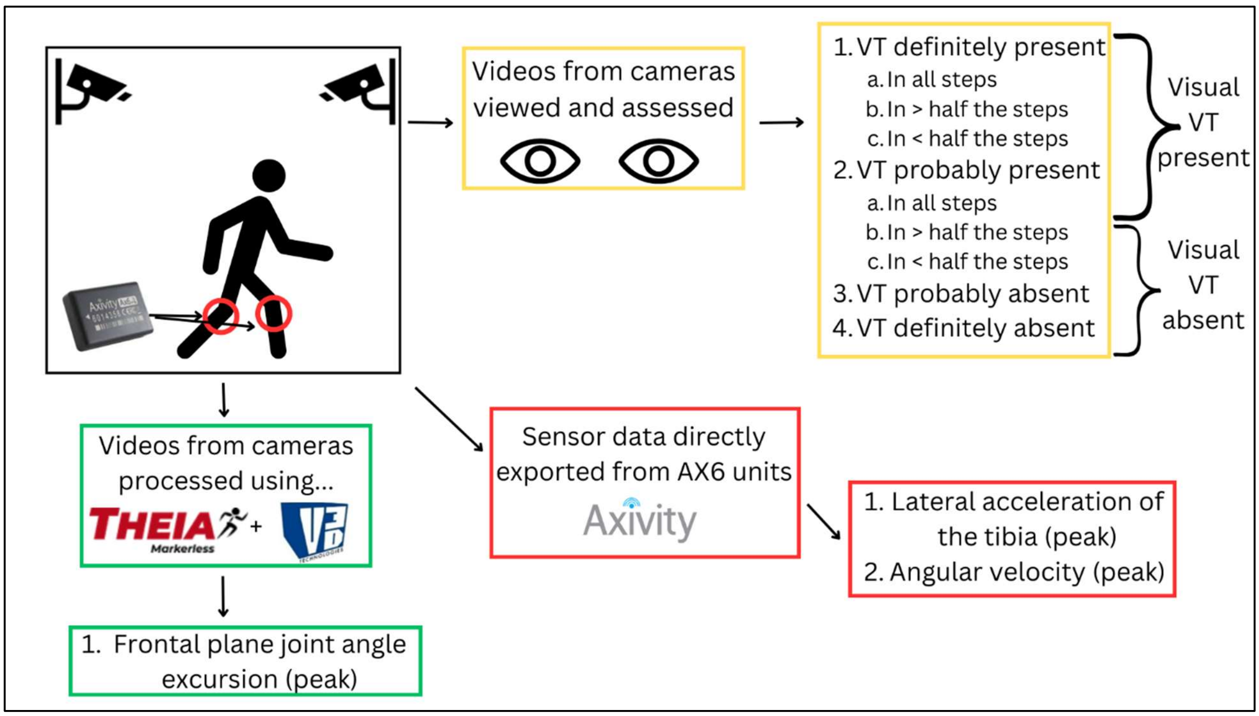

Figure 8: An illustration depicting the data collection protocol using the three VT assessment methods which are, from top to bottom: 1) Visual (yellow), 2) Wearable Sensors (red), and 3) Optical Motion Capture (green).

First, the unprocessed videos (i.e., no skeletal overlay) from the Theia systems' cameras were extracted and participant gait was visually observed and classified by two independent assessors, with a separate third assessor designated to resolve any disagreements between the primary assessors. Specifically, videos from cameras placed at frontal and superior angles relative to the participants' gait, as illustrated by Figure 9, were exported and assessed.

Figure 9: Images demonstrating the frontal and superior camera angles used for the visual assessment method. The image on the left depicts a participant walking towards the camera and the image on the right shows the same participant walking away from the camera.

The assessors underwent 3-4 training sessions for identifying visual VT using a smaller subset of videos that were not included in the study. The interrater reliability between the two main assessors after the training sessions was assessed using Cohen's kappa, which yielded a value of 0.71, indicating substantial agreement between the assessors.

The VT classification system was based on Wink *et al.*, 2017, involving four main categories: 'visible varus thrust definitely present', 'visible varus thrust probably present', 'visible varus thrust probably absent', and 'visible varus thrust definitely absent'. For the categories where

VT is determined to be 'definitely' or 'probably' present, knees were further classified based on whether the thrust was present during 'all steps,' 'greater than half (but not all) of steps,' and 'fewer than half of steps.' To support the primary goals of the current study, VT was then simplified into a binary variable where individuals who had 'definitely present' VT during any (>1) steps, and individuals with 'probably present' VT during **all** steps, were considered to have VT. Participants categorized in any other class were considered to not have VT. This class system was used to first separate the participants into preliminary groups before incorporating their quantitative data, to create groups with VT data that can then be analyzed.

In addition to the visual VT data, data was extracted from Axivity AX6 inertial sensors positioned medial to the tibial tuberosity. Accelerometer signals aligned to the mediolateral axis of the tibia were used to compute peak lateral acceleration (m/s^2) of the tibia during the first 30% of the stance phase. This variable represents one of the most commonly assessed inertial sensor-based markers of VT (Ogata *et al.*, 1997; Wada *et al.*, 2023). Gyroscope data were also extracted from the inertial sensors to provide data on the peak tibial frontal plane (or anteroposterior) angular velocity (degrees/s), as this is another variable of interest that has been used to define VT in previous studies (Tsurumiya *et al.*, 2021; Sato *et al.*, 2024).

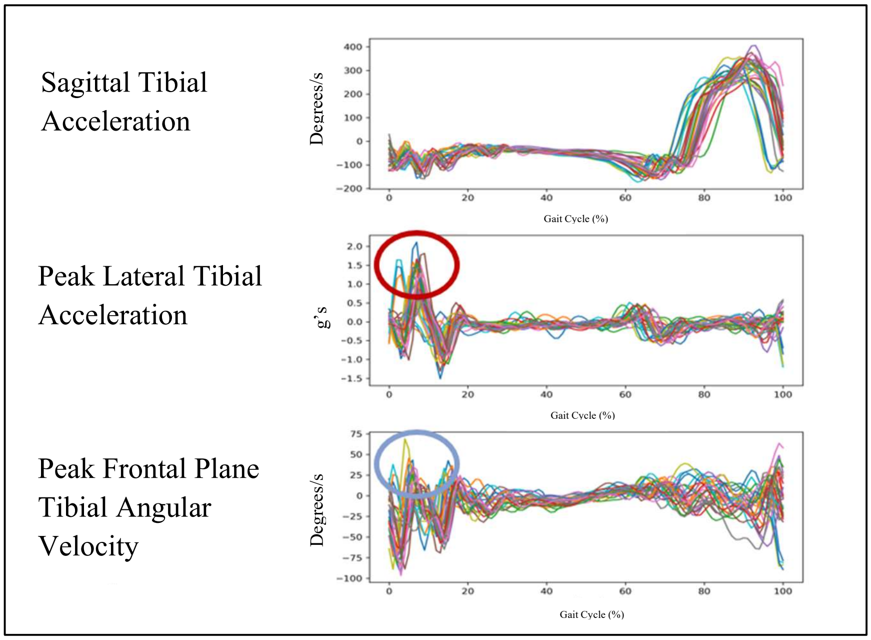

Figure 10: Image depicting sample data extracted from the wearable inertial measurement units. The top graph illustrates the acceleration of the tibia in the sagittal plane, which was used to confirm significant phases of gait. The second graph demonstrates the first variable of interest, the peak lateral tibial acceleration (g, later converted to m/s^2), which occurs in the first 30% of the gait cycle. The bottom graph depicts the second variable of interest, the peak frontal plane tibial angular velocity (degrees/s), as well as where it occurs within the first 30% of the gait cycle.

In parallel, the videos recorded from the cameras were synchronized and processed using the Theia3D software to develop kinematic models of the participants' gait. Theia3D applied virtual markers on a skeletal model of each participant and produced three-dimensional motion data files (C3D files). These files were then imported into Visual3D (V3D, C-Motion Inc., Kingston, ON), where spatiotemporal parameters and three-dimension joint kinematics were computed. From these data, peak frontal plane joint angle excursion (in degrees) during the first 30% of the stance phase was extracted and used as the primary VT variable from the motion capture system (Kuroyanagi *et al.*, 2012).

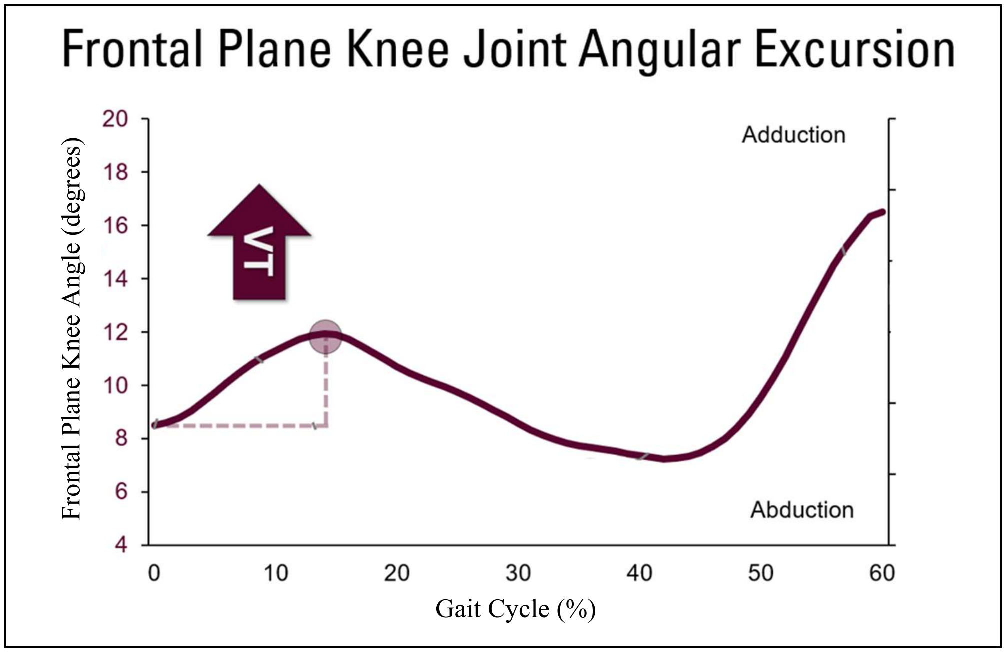

Figure 11: An illustration demonstrating the variable extracted from the optical motion capture system, frontal plane knee joint angular excursion (degrees).

Finally, a secondary stratification of visual VT data were undertaken to develop a smaller group whose VT status was more confidently and specifically assessed. This was done by applying a stricter criterion to the original binary visual VT ranking. This smaller subset was termed the 'Consensus Group' and was created by only classifying knees as having VT if both of the primary assessors rated them as definitely having VT in any number of their steps (Categories 1a, 1b, and 1c), and not having VT if both assessors rated the knee as a 3 (VT probably absent) or a 4 (VT definitely absent). This means that knees that were classed as 2a that were previously included in the 'VT present' group were then excluded. Similarly, the other categories in between that were previously included (i.e. 2b and 2c) were subsequently excluded from the Consensus Group. Overall, the 'Consensus Group' retained the binary outcome of the full participant pool's visual VT classification data, but was refined to include only participants for whom the primary assessors could definitively determine the presence or absence of VT. Corresponding wearable inertial sensor metrics and optical motion capture metrics were subsequently incorporated and analyzed, similarly to the large participant pool.

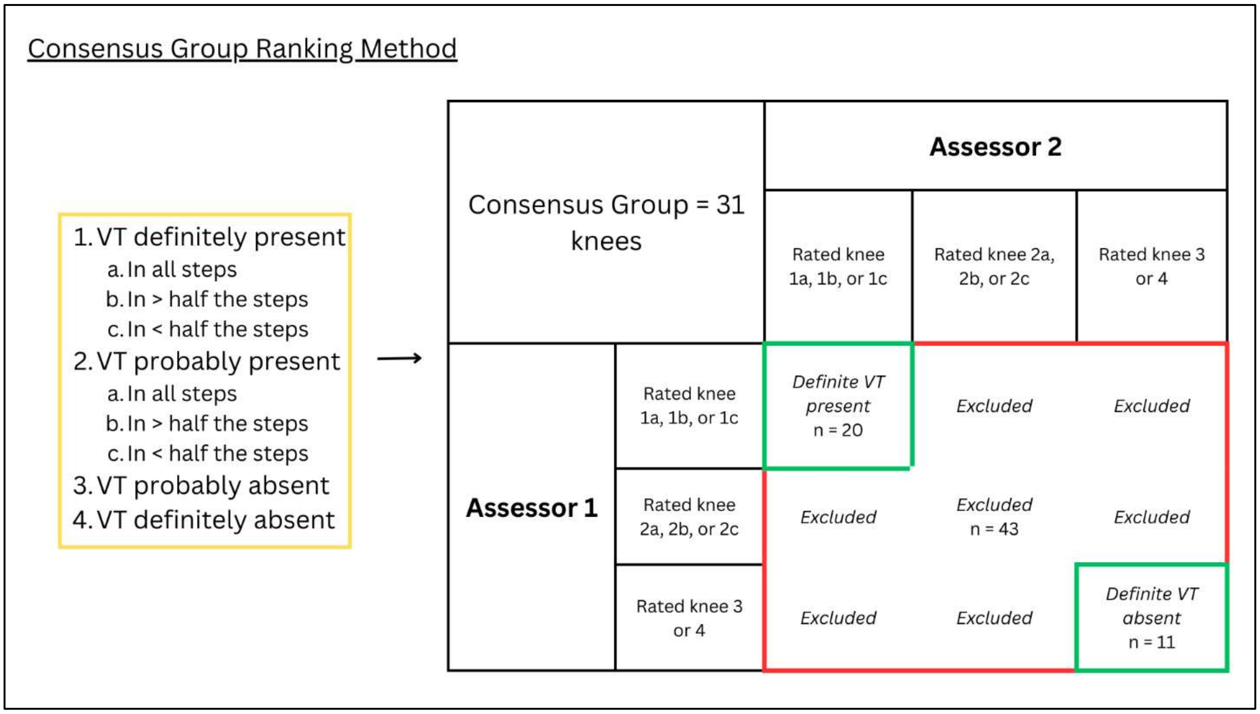

Figure 12: An illustration depicting the protocol for creating the Consensus Group, based on the rankings of the two primary assessors

4.5 – Statistical Analysis

To address both research questions, receiver operating characteristic (ROC) curves were generated to evaluate the discriminatory performance of each individual technological assessment method in classifying the presence of visually identified VT. ROC curves illustrate the diagnostic performance of a binary classifier across a range of threshold values by plotting the true positive rate (sensitivity) against the false positive rate (1 – specificity) (Park *et al.*, 2004). The true positive rate reflects the system's ability to correctly identify cases where VT is present, while the false positive rate reflects instances where VT is incorrectly identified (i.e., when visual assessment indicated no VT). Visual VT scores were treated as the binary outcome variable (0 = no VT, 1 = VT present), with the corresponding continuous values from each measurement system along the horizontal axis. In this context, the ROC analysis assessed how well each measurement system, motion capture and inertial sensors, could detect the presence of VT as defined by visual observation.

Each ROC curve was summarized by calculating the corresponding area under the curve (AUC), which quantifies overall classification performance. An AUC of 1.0 represents perfect classification, while an AUC of 0.5 reflects performance equivalent to random chance. For interpretative purposes, model performance was categorized using the following criteria: 0.90–1.00 = excellent, 0.80–0.89 = good, 0.70–0.79 = fair, 0.60–0.69 = poor, and <0.59 = failed discrimination (Nahm, 2022). For this study, the AUC values were computed using the trapezoidal rule.

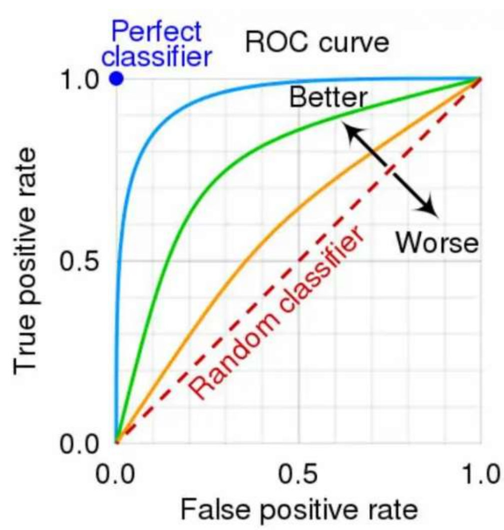

Figure 13: An illustration depicting examples of ROC curves at increasing levels of discriminatory strengths based on the area under their curves (Blue > Light blue > Green > Yellow > Red). **Note:** From *ROC curve and AUC – Evaluating model performance*, by İ. Kılıç, 2023, *Medium*.

https://medium.com/@ilyurek/roc-curve-and-auc-evaluating-model-performance-c2178008b02.

Additionally, a one-way Welch's ANOVA was conducted to evaluate the differences in the mean quantitative VT values (*e.g.*, peak lateral tibial accelerations, peak tibial frontal plane angular velocity, and peak knee frontal plane excursion) between the visual VT categories (VT present vs. VT absent). Welch's ANOVA was selected due to its robustness to unequal variances and sample sizes. An alpha level of 0.05 was used to determine statistical significance. This analysis will determine whether there are statistically significant differences between the visual VT classifications based on the measurement systems.

CHAPTER 5: RESULTS

An overview of participant characteristics and the number of knees classified as having VT present or absent is first provided for both the full sample and the sub-classified 'Consensus Group.' Results are then presented in the order of wearable sensor metrics (research question 1), followed by optical motion capture metrics (research question 2). Within each section, findings from the full participant pool are presented first, followed by results from the Consensus Group, and finally, the analyses with outliers removed. Detailed findings are described below, with summary tables provided at the end of the Results section (Tables 5.1–5.3).

5.1 – Participant Data Overview

Data from forty-five participants were initially collected, however, eight participants were excluded due to incomplete data or technical errors during data collection (*e.g.*, corrupted camera footage resulting in missing optical motion capture data, file corruption during wearable sensor data transfer, or gait speeds below 0.5 m/s). This resulted in a final sample of 37 eligible participants (24 females, 13 males) with a mean age of 64 ± 7 years. All participants completed their data collection trial within 6 days of their scheduled surgery date.

Data were processed and analyzed with all participant knees pooled, totaling a maximum of seventy-four knees assessed for each measurement method. Disagreements between the two primary assessors were found in forty-two of the seventy-four knees when applying the initial assessment criteria on the full participant pool. Following input from the third assessor, thirty-nine knees were then visually confirmed and classified as 'VT present,' and the remaining thirty-five were classified as 'VT absent.'

With the stricter 'Consensus Group' criteria applied, twenty of the original thirty-nine 'VT present' knees were determined to have 'definite VT present' by both assessors. Alternatively, eleven of the thirty-five original 'VT absent' knees were determined to have 'definite VT absent.' This resulted in a total of thirty-one knees in the Consensus Group.

5.2 – Wearable Sensor Results

5.2.1 – Peak Lateral Tibial Acceleration

For the first research question, the peak lateral acceleration of the tibia was calculated for all 74 knees. The mean acceleration for knee in the 'VT present' group was 0.90 ± 0.34 m/s^2, while the 'VT absent' group had a mean of 0.83 ± 0.42 m/s^2 (Figure 14). A one-way Welch's ANOVA indicated no significant difference between groups ($p = 0.47$). Similarly, the AUC was 0.56 (Figure 15), indicating this metric failed to have any discriminatory capacity when examining all knees.

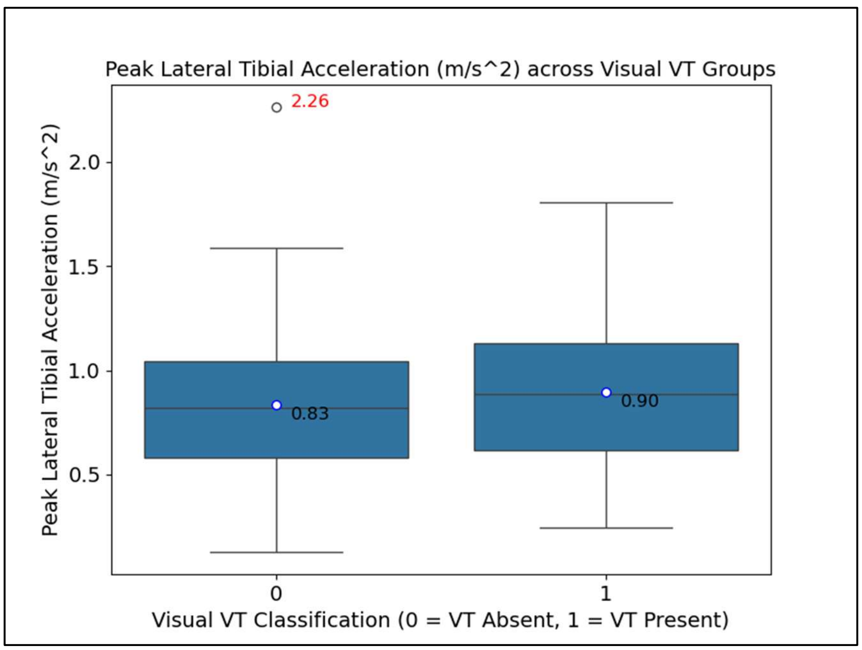

Figure 14: Boxplot showing the distribution of peak lateral tibial acceleration (m/s^2) across the two groups, with Visual VT classification (0 = VT absent, 1 = VT present) on the x-axis. The boxes represent the interquartile range (IQR; 25^{th} to 75^{th} percentile), with the horizontal line indicating the median. Whiskers extend to the smallest and largest values within 1.5 x IQR. Dots with red labels represent the individual outliers beyond 1.5 x IQR, and dots with black labels represent the mean values for each group.

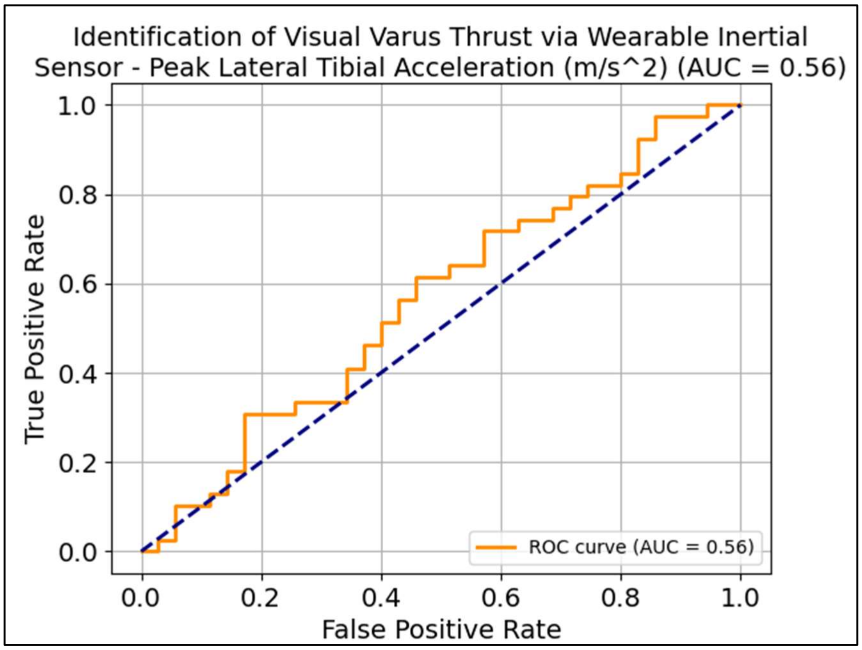

Figure 15: The ROC curve illustrates the diagnostic performance of the tibial inertial sensor (peak lateral tibial acceleration in m/s²) in detecting varus thrust. The area under the curve (AUC) is 0.56, indicating failure in discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

Consensus Group. Following sub-classification into the Consensus Group, peak lateral tibial acceleration values were obtained from 20 knees that were rated as having 'definite VT present' and 11 knees classified in the 'definite VT absent' group. The mean peak acceleration was 0.96 ± 0.33 m/s^2 for the 'definite VT present' group and 0.78 ± 0.51 m/s^2 for the 'definite VT absent' group (Figure 16). A one-way Welch's ANOVA indicated no statistical difference between groups (p = 0.33). The corresponding AUC was 0.75, indicating moderate discriminatory capacity when only knees with definite VT presence or absence were examined (Figure 17).

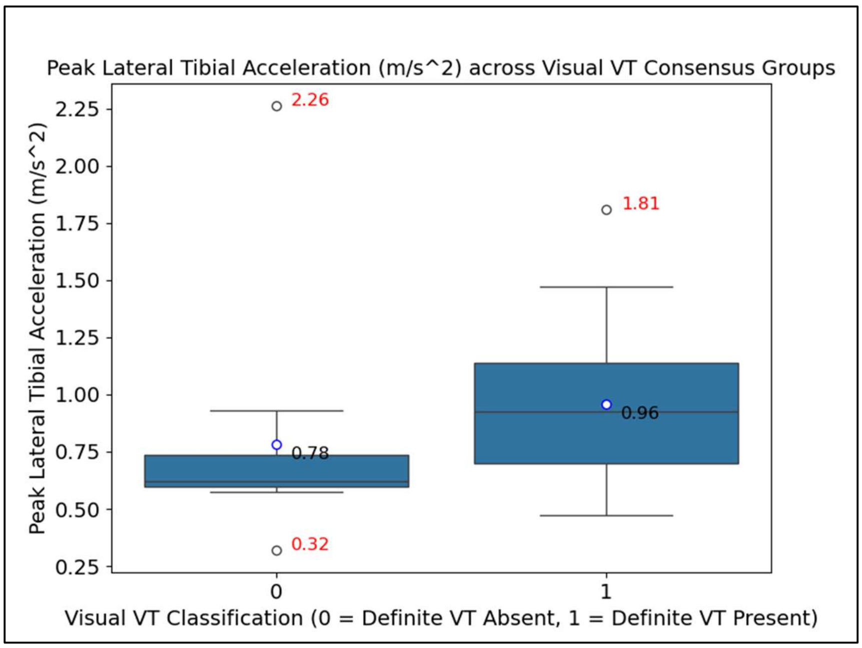

Figure 16: Boxplot showing the distribution of peak lateral tibial acceleration (m/s^2) across the two consensus groups, with Visual VT classification (0 = definite VT absent, 1 = definite VT present) on the x-axis. The boxes represent the interquartile range (IQR; 25th to 75th percentile), with the horizontal line indicating the median. Whiskers extend to the smallest and largest values within 1.5 x IQR. Dots with red labels represent the individual outliers beyond 1.5 x IQR, and dots with black labels represent the mean values for each group.

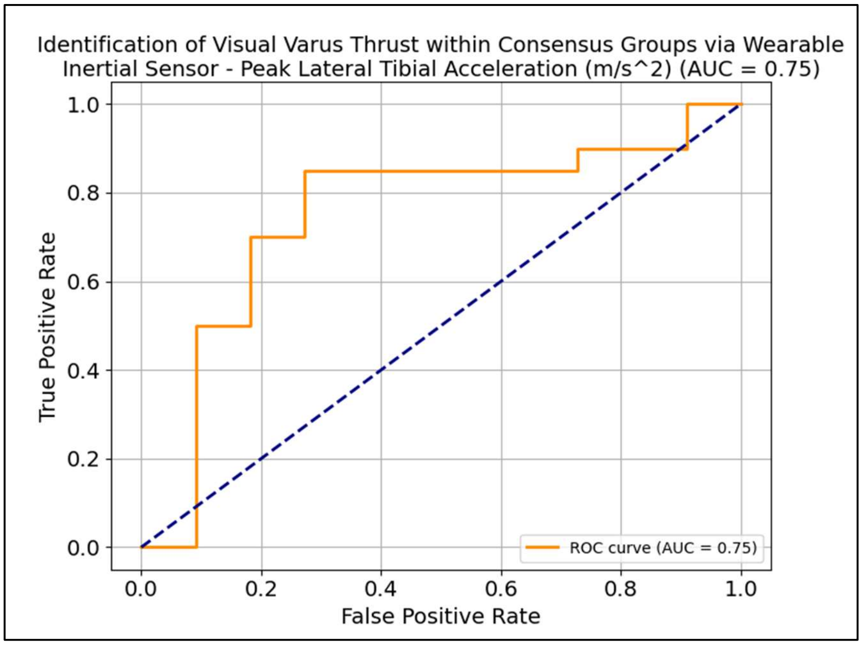

Figure 17: The ROC curve illustrates the diagnostic performance of the wearable sensor (peak lateral tibial acceleration in m/s^2*) in detecting varus thrust, for the consensus group. The area under the curve (AUC) is 0.75 indicating fair discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).*

While the Consensus Group data showed improvements in both AUC value and group separation, boxplots in Figure 12 identified three outliers across the two groups. After removing these outliers, the AUC increased to 0.80 (Figure 18), indicating good discriminatory capacity and a statistically significant difference between groups ($p = 0.003$).

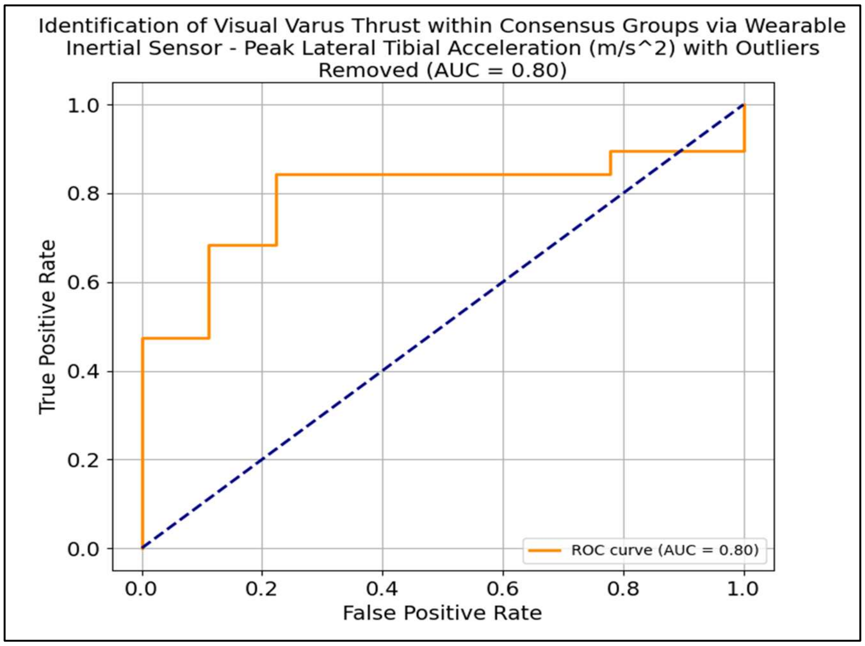

Figure 18: The ROC curve illustrates the diagnostic performance of the wearable sensor (peak lateral tibial acceleration in m/s²) in detecting varus thrust, for the consensus group with outliers removed. The area under the curve (AUC) is 0.80 indicating good discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

5.2.2 – Peak Frontal Plane Tibial Angular Velocity

Gyroscopic data from the wearable sensors were used to calculate peak frontal plane angular velocity of the tibia for the full participant pool. The 'VT present' group had a mean angular velocity of 24.7 ± 28.3 degrees/s, while the 'VT absent' group averaged 28.8 ± 29.0 degrees/s (Figure 19). A one-way Welch's ANOVA indicated no significant difference between groups ($p = 0.54$). The corresponding AUC was 0.43, indicating no discriminatory capacity (Figure 20).

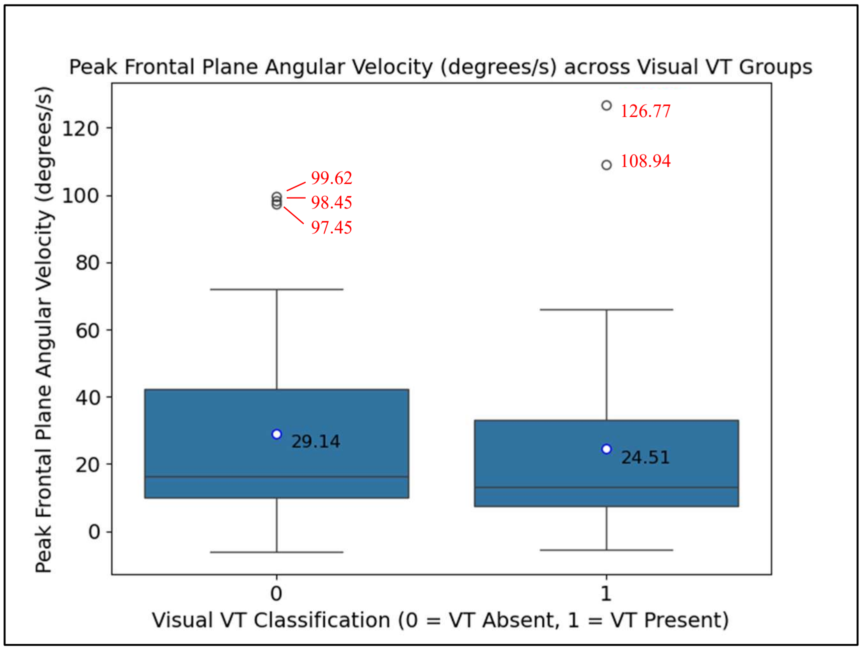

Figure 19: Boxplot showing the distribution of peak frontal plane tibial angular velocity (degrees/s) across the two groups, with Visual VT classification (0 = VT absent, 1 = VT present) on the x-axis. The boxes represent the interquartile range (IQR; 25th to 75th percentile), with the horizontal line indicating the median. Whiskers extend to the smallest and largest values within 1.5 x IQR. Dots with red labels represent the individual outliers beyond 1.5 x IQR, and dots with black labels represent the mean values for each group.

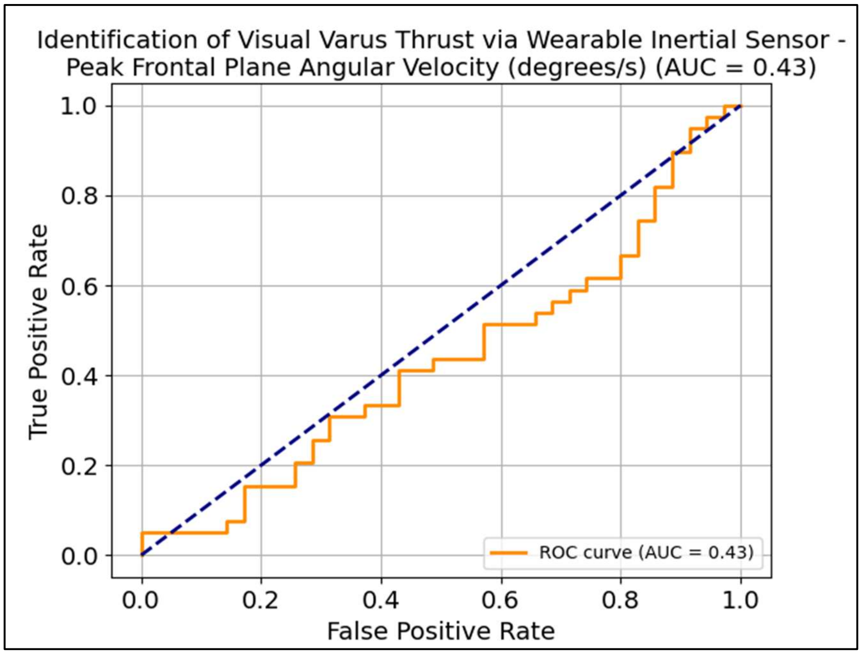

Figure 20: The ROC curve illustrates the diagnostic performance of the wearable inertial sensor (peak frontal plane tibial angular velocity in degrees/s) in detecting varus thrust. The area under the curve (AUC) is 0.43, indicating failure in discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

Consensus Group. Within the Consensus Group sub-classification, the mean peak frontal plane tibial angular velocity from wearable sensors was 30.0 ± 29.7 degrees/s for the 'definite VT present' group and 34.4 ± 37.1 degrees/s for the 'definite VT absent' group (Figure 21). A one-way Welch's ANOVA indicated no significant difference between groups (p = 0.74). This metric also showed no discriminatory capacity, with an AUC of 0.47 (Figure 22). Removal of a single outlier had a minimal effect on the results (Figure A4; AUC = 0.44; p = 0.44).

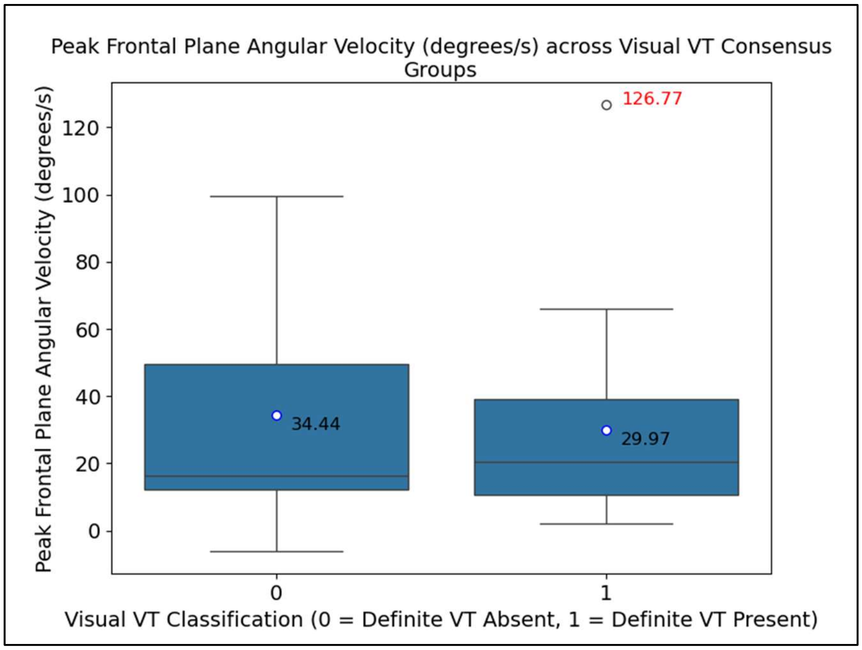

Figure 21: Boxplot showing the distribution of peak frontal plane tibial angular velocity (degrees/s) across the two consensus groups, with Visual VT classification (0 = definite VT absent, 1 = definite VT present) on the x-axis. The boxes represent the interquartile range (IQR; 25th to 75th percentile), with the horizontal line indicating the median. Whiskers extend to the smallest and largest values within 1.5 x IQR. Dots with red labels represent the individual outliers beyond 1.5 x IQR, and dots with black labels represent the mean values for each group.

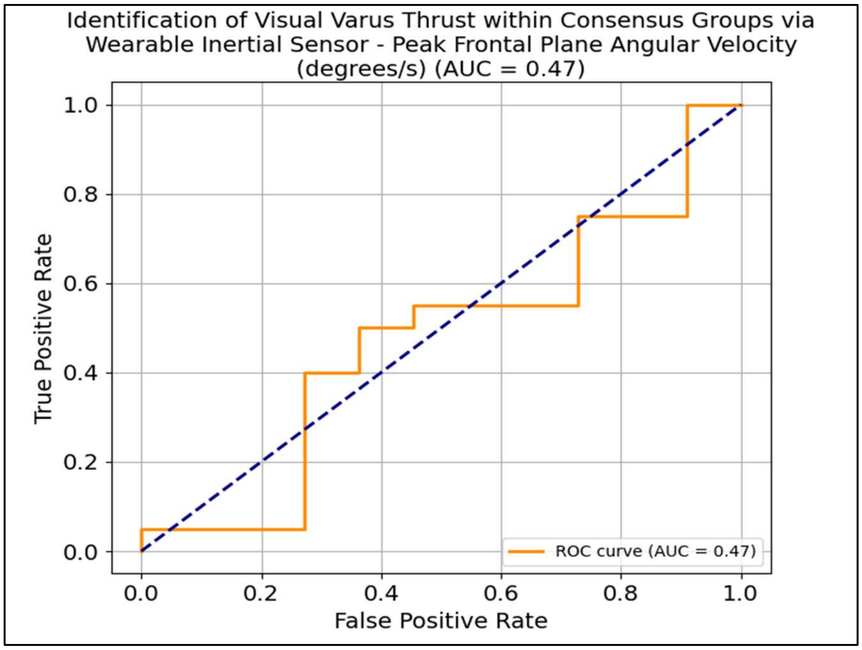

Figure 22: The ROC curve illustrates the diagnostic performance of the wearable sensor system (peak frontal plane tibial angular velocity in degrees/s) in detecting varus thrust, for the consensus group. The area under the curve (AUC) is 0.47, indicating a discriminatory ability worse than random chance. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

5.3 – Optical Motion Capture Results

Regarding the second research question, frontal plane knee joint angle excursion was calculated for 64 knees, with 10 being excluded from the full participant pool due to missing camera data. Of the remaining knees, 32 were classified as having visually observable VT and 32 as not having observable VT. The 'VT present' group showed an average excursion of 2.5 ± 1.2 degrees compared to 2.0 ± 1.2 degrees in the 'VT absent' group (Figure 23). A one-way Welch's ANOVA indicated no significant difference between groups (p = 0.11). The AUC was 0.60, indicating poor discriminatory ability (Figure 24).

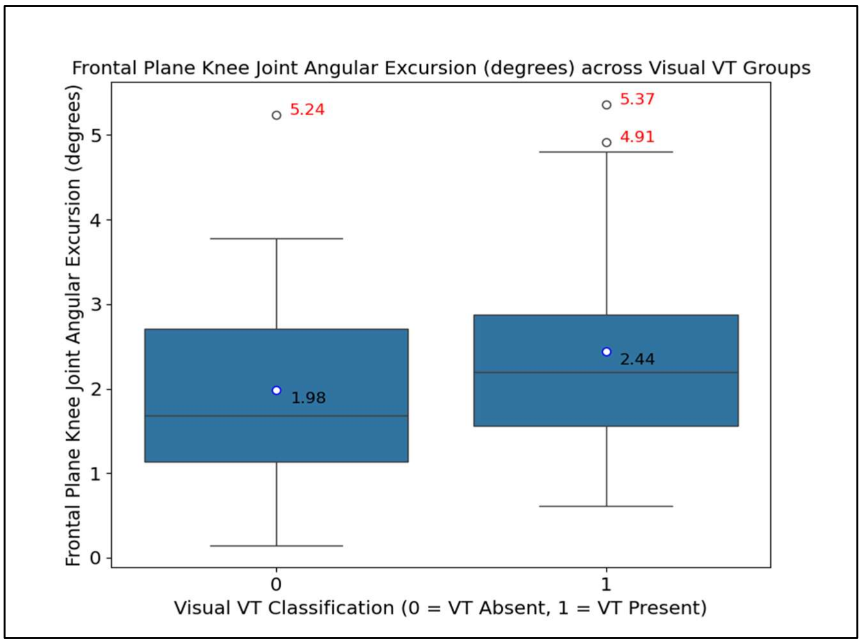

Figure 23: Boxplot showing the distribution of frontal plane knee joint angular excursion (degrees) across the two groups, with Visual VT classification (0 = VT absent, 1 = VT present) on the x-axis. The boxes represent the interquartile range (IQR; 25th to 75th percentile), with the horizontal line indicating the median. Whiskers extend to the smallest and largest values within 1.5 x IQR. Dots with red labels represent the individual outliers beyond 1.5 x IQR, and dots with black labels represent the mean values for each group.

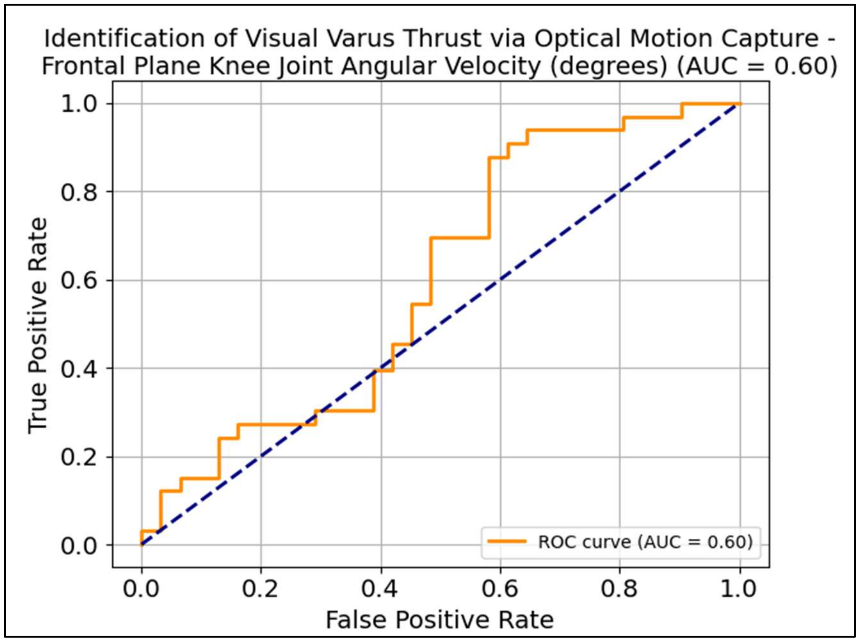

Figure 24: The ROC curve illustrates the diagnostic performance of the optical motion capture system (frontal plane knee joint angular excursion in degrees) in detecting varus thrust. The area under the curve (AUC) is 0.60, indicating poor discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

Consensus Group. For the optical motion capture data, the Consensus Group included 28 knees, from the 64 knees with available optical motion capture data. 17 of these knees were classified as having 'definite VT present' and 11 were classified in the 'definite VT absent' group. The 'definite VT present' group had a mean frontal plane knee joint angle excursion of 2.2 ± 0.9 degrees, while the 'definite VT absent' group averaged 1.5 ± 0.9 degrees (Figure 25). A one-way Welch's ANOVA indicated a near-statistical difference between groups (p = 0.08). However, the AUC was 0.65, indicating poor discriminatory ability (Figure 26). Removal of a single outlier did not alter this interpretation (Figure A5; p = 0.14; AUC = 0.65).

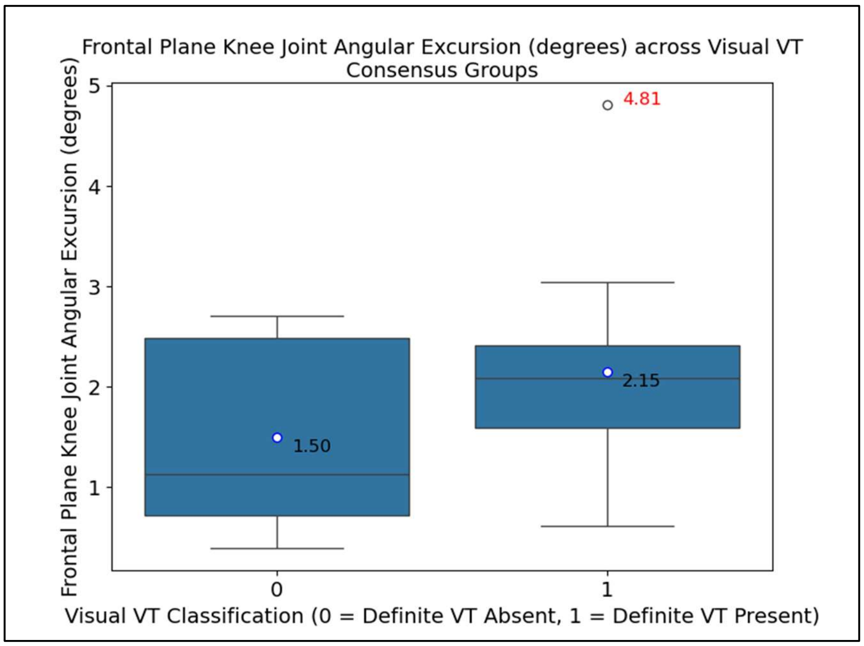

Figure 25: Boxplot showing the distribution of frontal plane knee joint angular excursion (degrees) across the two consensus groups, with Visual VT classification (0 = definite VT absent, 1 = definite VT present) on the x-axis. The boxes represent the interquartile range (IQR; 25^{th} to 75^{th} percentile), with the horizontal line indicating the median. Whiskers extend to the smallest and largest values within 1.5 x IQR. Dots with red labels represent the individual outliers beyond 1.5 x IQR, and dots with black labels represent the mean values for each group.

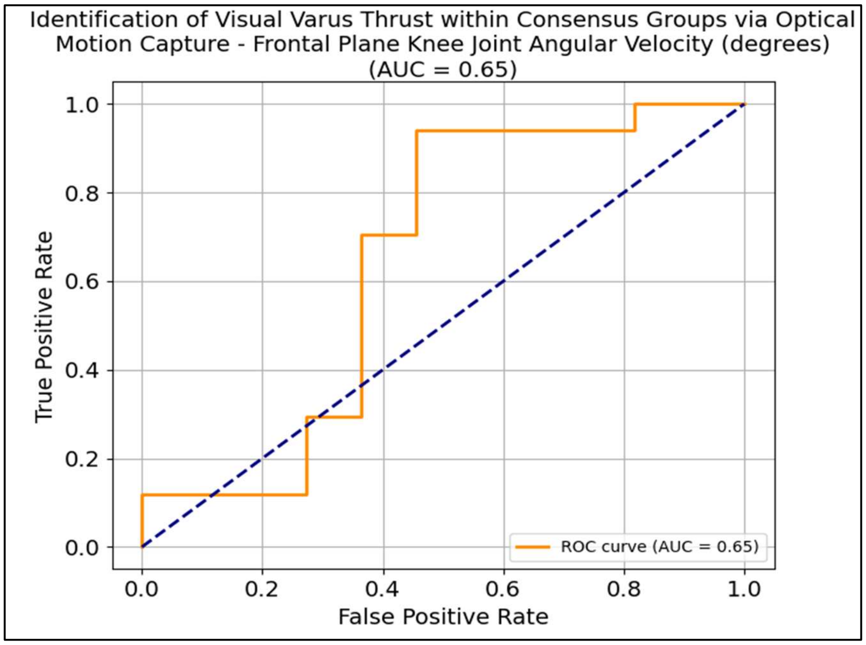

Figure 26: The ROC curve illustrates the diagnostic performance of the optical motion capture system (frontal plane knee joint angular excursion in degrees) in detecting varus thrust, for the consensus group. The area under the curve (AUC) is 0.65, indicating poor discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

Table 5.1: A summary of the results for the full participant pool, using both methods of measurement.

Measurement Method	**Groups**	**Mean ± SD**	**Statistics**
Wearable Sensor: Peak Lateral Tibial Acceleration	VT present (n = 39)	0.90 ± 0.34 m/s^2	F (1, 68.0) = 0.53; *p* = 0.47; ES = 0.19; AUC = 0.56
	VT absent (n = 35)	0.83 ± 0.42 m/s^2	
Wearable Sensor: Peak Frontal Plane Tibial Angular Velocity	VT present (n = 39)	24.7 ± 28.3 deg/s	F (1 ,71.9) = 0.38; *p* = 0.54; ES = -0.14; AUC = 0.43
	VT absent (n = 35)	28.8 ± 29.0 deg/s	
Optical Motion Capture: Frontal Plane Knee Joint Angle Excursion	VT present (n = 32)	2.5 ± 1.2 deg	F (1, 62.0) = 2.56; *p* = 0.11; ES = 0.42 AUC = 0.60
	VT absent (n = 32)	2.0 ± 1.2 deg	

Abbreviations: standard deviation (SD), varus thrust (VT), Cohen's *d* effect size (ES), area under the curve (AUC)

Table 5.2: A summary of the results for the consensus participant pool, using both methods of measurement.

Measurement Method	**Groups**	**Mean ± SD**	**F-value**
Wearable Sensor: Peak Lateral Tibial Acceleration	Definite VT present (n = 20)	0.96 ± 0.33 m/s^2	F (1, 14.6) = 1.04; *p* = 0.33; ES = 1.1; AUC = 0.75
	Definite VT absent (n = 11)	0.78 ± 0.51 m/s^2	
Wearable Sensor: Peak Frontal Plane Tibial Angular Velocity	Definite VT present (n = 20)	30.0 ± 29.7 deg/s	F (1, 17.2) = 0.12; *p* = 0.74; ES = -0.32; AUC = 0.47
	Definite VT absent (n = 11)	34.4 ± 37.1 deg/s	
Optical Motion Capture: Frontal Plane Knee Joint Angle Excursion	Definite VT present (n = 17)	2.2 ± 0.9 deg	F (1, 20.8) = 3.48; *p* = 0.08; ES = 0.78; AUC = 0.65
	Definite VT absent (n = 11)	1.5 ± 0.9 deg	

Abbreviations: standard deviation (SD), varus thrust (VT), Cohen's *d* effect size (ES), area under the curve (AUC)

Table 5.3: A summary of the results for the consensus participant pool with outliers removed, using both methods of measurement.

Measurement Method	**Groups**	**Mean ± SD**	**F-value**
Wearable Sensor: Peak Lateral Tibial Acceleration	Definite VT present (n = 19)	0.91 ± 0.27 m/s²	F (1, 25.9) = 11.1; ***p* = 0.003; ES = 2.86; AUC = 0.80**
	Definite VT absent (n = 9)	0.67 ± 0.12 m/s²	
Wearable Sensor: Peak Frontal Plane Tibial Angular Velocity	Definite VT present (n = 19)	24.9 ± 19.6 deg/s	F (1, 13.3) = 0.63; *p* = 0.44; ES = -0.90; AUC = 0.44
	Definite VT absent (n = 11)	34.4 ± 37.1 deg/s	
Optical Motion Capture: Frontal Plane Knee Joint Angle Excursion	Definite VT present (n = 16)	2.0 ± 0.6 deg	F (1, 15.2) = 2.44; *p* = 0.14; ES = 0.67; AUC = 0.62
	Definite VT absent (n = 11)	1.5 ± 0.9 deg	

Abbreviations: standard deviation (SD), varus thrust (VT), Cohen's *d* effect size (ES), area under the curve (AUC)

CHAPTER 6: DISCUSSION

The present study assessed whether peak lateral tibial acceleration and peak frontal plane tibial angular velocity measured by wearable sensors, and frontal plane angular excursion from markerless motion capture, align with visually assessed VT during gait in older adults with knee osteoarthritis. This was carried out to address the existing gap in research in evaluating visually confirmed VT with wearable sensor and markerless motion capture data, simultaneously. In this study, visual VT was observed in 57% of the knees assessed, yet none of the quantitative metrics, whether derived from wearable sensors or markerless motion capture, demonstrated meaningful discriminatory ability across the full dataset (AUC = 0.43-0.60). In contrast, when comparisons were limited to a more refined subset of clearly present versus clearly absent VT, the 'Consensus Group,' the distinction between groups became more apparent. This was particularly evident for peak lateral tibial acceleration, which showed a large effect size and reached an AUC value of 0.80 after outlier removal. These findings demonstrate the potential for wearable sensors to quantitatively capture aspects of VT that clinicians have traditionally identified through subjective visual observation but also underscore the inherent variability and challenges of VT assessment.

A key finding of this study was the overall lack of discriminatory ability across all measurement systems when applied to the full dataset. None of the quantitative VT metrics, whether derived from wearable sensors or optical motion capture, demonstrated statistically significant differences between knees classified as having VT versus those without (p = 0.11-0.54). This was particularly evident in the wearable sensor metrics, which exhibited high within-group variability and substantial overlap between VT categories, as illustrated in Figures 14 and 19. Additionally, the corresponding ROC curves yielded low AUC values (0.43 and 0.56), further highlighting the limited discriminatory performance of these metrics. Although frontal plane knee angle excursion from the optical motion capture system yielded a slightly higher AUC (0.60), it still falls at the lower boundary of what is typically considered poor discriminatory capacity. These results prompt the question of whether the lack of group separation is primarily due to limitations in the quantitative VT markers or the inherent difficulty of using visual VT as a reference standard.

Using visual VT as the gold standard criterion presents inherent challenges, particularly when classifying its presence on a binary scale. While various methods have been employed, the approach adopted in the current study is one of the most well-defined, evolving from the basic presence/absence rating (Chang *et al.*, 2004) to a more detailed system incorporating confidence levels and the number of observed steps (Wink *et al.*, 2017; Wink *et al.*, 2019). Nevertheless, this system still requires mid-range classifications to ultimately be dichotomized as either VT present or absent, which introduces subjectivity and uncertainty. Other studies have implemented similar Likert-scale approaches (*e.g.*, 'very confident,' 'somewhat confident,' 'not very confident,' or 'not at all confident') but typically set the threshold for VT presence at 'very confident' (Chang *et al.*, 2013; Tsukamoto *et al.*, 2021). Despite these efforts to define the presence of VT, there remains a need for more objective methods to distinguish not only its absence but also the uncertainty that exists between clear categories.

The development of the 'Consensus Group' sub-classification in the current study addressed this issue by isolating only the most obvious cases, enabling a more confident examination of VT presence and absence. This approach is similar to that of Chang *et al.* (2013), who defined VT presence exclusively in cases where raters were "very confident" and compared these to cases deemed 'very confident' in the absence of VT. However, their study relied on a single rater at a time, and the criteria for defining group membership were inconsistently described, making the classification approach difficult to interpret or replicate. A similar method was used more recently by Tsukamoto *et al.* (2021), who divided participants into three groups: 'clearly present VT,' 'ambiguous,' and 'clearly absent VT.' Yet, as with Chang *et al.* (2013), this study also relied on a single rater and provided limited detail regarding the rating process, again reducing replicability. Notably, these studies reported substantial differences in the number of individuals classified as having 'clearly present VT.' When examining only those with Kellgren–Lawrence severity grades of 3 or 4, comparable to the 'end-stage' cohort in the current study, Tsukamoto *et al.* (2021) reported 57% and Chang *et al.* (2013) reported 37%, both notably higher than the 27% identified within the current Consensus Group. While these inconsistencies underscore the broader challenge of relying on visual VT assessment, they also highlight the potential value of defining more definitive subgroups, rather than relying on a single binary classification, as implemented in the current study.

Within the context of the Consensus Group, diagnostic performance improved across all three quantitative variables. Most notably, peak lateral tibial acceleration showed the largest increase, reaching an AUC of 0.75, and 0.80 when outliers were removed, along with large effect sizes between groups (Cohen's d = 1.1-2.8). These results suggest moderate to good discriminatory ability for detecting VT when restricted to cases with high visual classification confidence. Although the other two metrics also showed modest improvements in AUC within this refined sample, their gains were considerably smaller and did not approach the performance of peak lateral acceleration. Furthermore, none of the variables in the current study matched the level of diagnostic accuracy previously reported by Tsukamoto *et al.* (2021), who found an AUC of 0.9 for knee angular velocity derived from frontal plane knee joint angles, a less commonly used VT marker (Mahmoudian *et al.*, 2016; Espinosa *et al.*, 2020). While the reasons for this discrepancy remain unclear, several methodological differences between studies may explain the variation. These include differences in walking distance (*e.g.*, only a single pass across a 10-metre walkway in Tsukamoto *et al.,* 2021.), variations in the definition and computation of VT metrics, and, as previously discussed, differences in the visual rating systems used for classification.

This study was the first to examine wearable inertial sensor markers of VT in direct comparison with markerless optical motion capture, and the findings suggest that peak lateral tibial acceleration may be a more sensitive indicator of visually defined VT than angular rotational movements. Given that VT is characterized by a brief, abrupt lateral movement of the knee during weight acceptance in gait, acceleration-based measures may better capture its dynamic nature. Specifically, peak lateral tibial acceleration reflects how quickly the knee deviates laterally, potentially aligning more closely with the visual cues that clinicians rely on during observation. This interpretation is supported by similarities in the literature from both visual VT (Chang *et al.*, 2014; Fukutani *et al.*, 2016) and acceleration-based VT metrics (Ishii *et al.*, 2020; Misu *et al.*, 2022; Tsukamoto *et al.*, 2023) which have independently been linked to knee OA severity, symptomatology, and progression. These parallels reinforce the potential value of lateral acceleration as a clinically meaningful and biomechanically relevant marker of VT.

In contrast, measures such as peak frontal plane angular velocity and frontal plane angular excursion may have limitations for several reasons. First, previous work from our lab (Ruder *et al.*, 2023) has shown that waveform features and discrete peaks derived from frontal plane angular velocity data demonstrate lower reliability than those based on lateral acceleration (*e.g.*, intraclass correlation coefficients: frontal plane angular velocity = 0.74–0.81 vs. lateral acceleration = 0.83–0.90). This reduced reliability likely contributes to greater variability in the data and, in turn, weaker discriminatory performance. Second, while motion capture-based frontal plane angular excursion of the upper tibia captures the displacement of the knee from its neutral alignment, it may not fully reflect the abrupt, transient motion characteristic of VT. This limitation is evident in the current findings, where between-group differences in excursion were minimal, approximately 0.5 degrees, suggesting that this measure may lack the sensitivity needed to distinguish VT from non-VT gait patterns. Taken together, these findings may help explain why these variables underperformed relative to peak lateral tibial acceleration in identifying visually defined VT, and why lateral acceleration may better capture and characterize the rapid deviation and movement typical of varus thrust.

6.1 – Limitations

The primary limitation in this study, consistent with other research in this area, was the subjective nature of visual VT assessment. Factors such as a slightly elevated and downward-angled camera position, along with non-standardized clothing, may have limited the assessors' ability to clearly visualize and rate VT presence. Although all three assessors completed three to four training sessions and the two primary assessors demonstrated strong inter-rater reliability (Cohen's kappa = 0.71), they did not have the same level of prior experience in VT assessment as orthopaedic surgeons or other expert raters used in similar studies (*e.g.*, Tsukamoto *et al.*, 2021; Chang *et al.*, 2013).

A second limitation involves the extraction of discrete parameters from complex gait waveforms. Although peak lateral accelerations and angular velocities were extracted from the first 30% of the stance phase, similar to other studies in this field (Kuroyanagi *et al*., 2012; Tsukamoto *et al.*, 2021), these peaks are not always easily defined. Some waveforms exhibit multiple oscillations, and the peak values may not align precisely with mid-stance loading, when visual VT is typically observed. More advanced analytical approaches, such as principal component analysis, may offer improved sensitivity by capturing the underlying structure of frontal plane deviations over time.

Finally, although all participants had a diagnosis of knee OA in at least one knee, data from both knees were included in the analysis. It remains unclear whether the presence of OA or VT in one knee may influence gait mechanics or VT expression in the contralateral limb. This may have introduced variability and reduced discriminatory power, although similar approaches have been taken in previous studies (*e.g.*, Chang *et al.*, 2013; Tsukamoto *et al.*, 2021). Additionally, while all participants were at or approaching end-stage disease, we did not adjust for individual gait characteristics such as walking speed, trunk lean, or foot progression angle. These unaccounted-for gait modifications may contribute to variability in VT expression, highlighting the ongoing difficulty of making individual-level VT classifications despite promising group-level trends.

6.2 – Significance and Future Directions

This study aimed to advance the understanding of varus thrust (VT) in individuals with knee osteoarthritis by employing wearable sensors and markerless motion capture technology to attempt to evaluate and quantify it. By assigning metric values to visually assessed VT, the findings contribute to ongoing efforts to better characterize this clinically relevant yet poorly defined gait phenomenon. A clearer and more objective understanding of VT may not only support future research into OA-related gait impairments but also inform clinical assessment practices and the development of targeted therapeutic strategies. Integrating wearable sensors into VT assessment offers a promising step toward more accessible, scalable, and quantitative evaluation methods in both research and clinical settings.

Future work should focus on optimizing data processing methods to enhance the reliability and consistency of VT measurements. Similar efforts are also needed to develop and implement robust training programs for visual VT assessment, in order to improve rater consistency and minimize subjectivity. Expanding the number and expertise of assessors in future studies will further strengthen the quality of visual classification. In addition, the repeatability and clinical utility of the VT threshold identified in this study should be validated in larger, independent cohorts. Expanding research to include more diverse populations in terms of ethnicity, sex, and disease severity will also improve the generalizability and translational impact of future findings.

Accurately identifying and quantifying varus thrust remains an essential objective, given its strong links to medial knee OA disease progression and its indications about knee joint loading and instability. By capturing the brief but significant deviations in frontal plane knee alignment during gait, VT assessments can provide valuable biomechanical insight and inform both clinical decision-making and personalized intervention strategies.

CHAPTER 7: CONCLUSION

This project aimed to fill a knowledge gap by combining three methods of varus thrust measurement – visual assessment, a single wearable inertial sensor, and a 10-camera markerless optical motion capture system. A binary classification of VT presence was obtained through visual assessment as the basis of this study. Variables of interest were knee joint peak lateral tibial acceleration and peak frontal plane tibial angular velocity, which were measured by wearable sensors, and peak knee joint angle excursion, which was computed by the optical motion capture system.

Findings indicated poor discriminatory capacity of all measurement variables when assessing a group that included knees with ambiguous VT presentation and statistical outliers. However, once those ambiguous and atypical cases were filtered out, peak lateral acceleration emerged as the most effective and statistically significant method for distinguishing VT. This finding is consistent with previous research citing peak lateral tibial acceleration as a key biomechanical marker and component of VT (Iwama *et al.*, 2021; Tsukamoto *et al.*, 2023; Tsurumiya *et al.*, 2021), reinforcing its relevance for future research and clinical application.

Importantly, this study did not simply aim to validate objective VT markers against visual ratings, but to establish whether the phenomena observed by experienced clinicians and trained researchers can be quantified. Our results indicate that objective measures, particularly peak lateral tibial acceleration, effectively discriminate clear cases of VT presence and absence, yet fail to differentiate visually ambiguous presentations. Thus, the lack of separation in these intermediate cases does not necessarily reflect a limitation of the sensor-based methods but rather highlights the subjective and variable nature of visual VT assessment when presentation is subtle. While visual evaluation remains a clinically intuitive and accessible tool, identifying peak lateral tibial acceleration as a reliable, objective marker underscores the potential of wearable technology to enhance diagnostic precision and biomechanical monitoring. These insights lay the groundwork for refining quantitative thresholds, advancing data-processing algorithms, and integrating sensor-based assessments into future prospective studies of disease progression and treatment response.

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APPENDIX

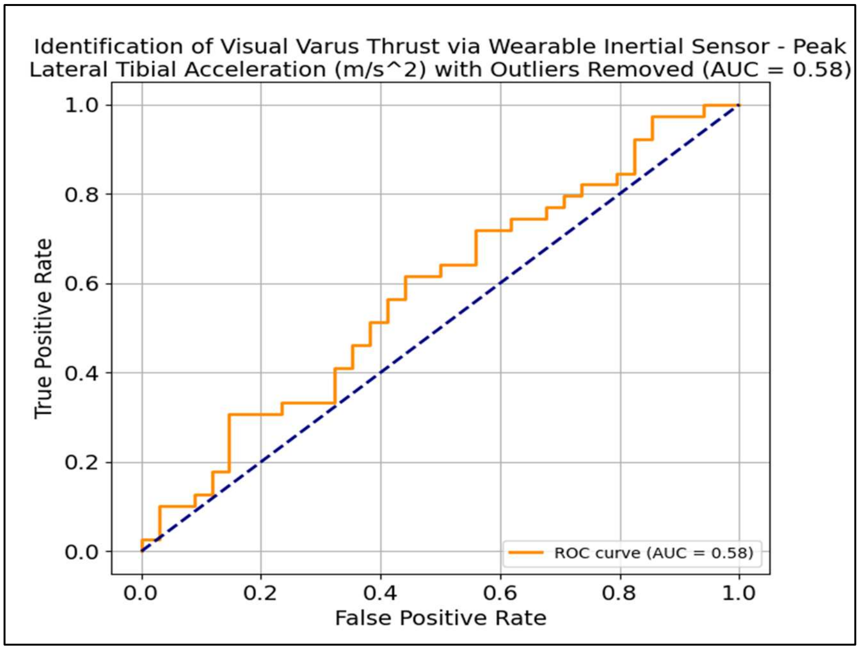

Figure A1: The ROC curve illustrates the diagnostic performance of the wearable inertial sensor system (accelerometer) in detecting varus thrust, for the full participant pool with outliers removed. The area under the curve (AUC) is 0.58, indicating failure in discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

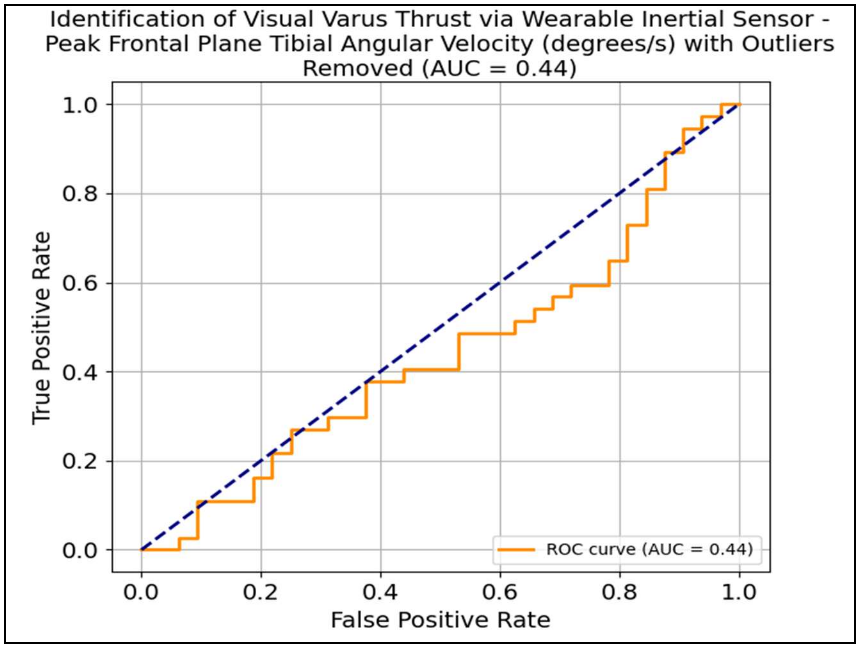

Figure A2: The ROC curve illustrates the diagnostic performance of the wearable inertial sensor system (gyroscope) in detecting varus thrust, for the full participant pool with outliers removed. The area under the curve (AUC) is 0.44, indicating a discriminatory ability worse than random chance. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

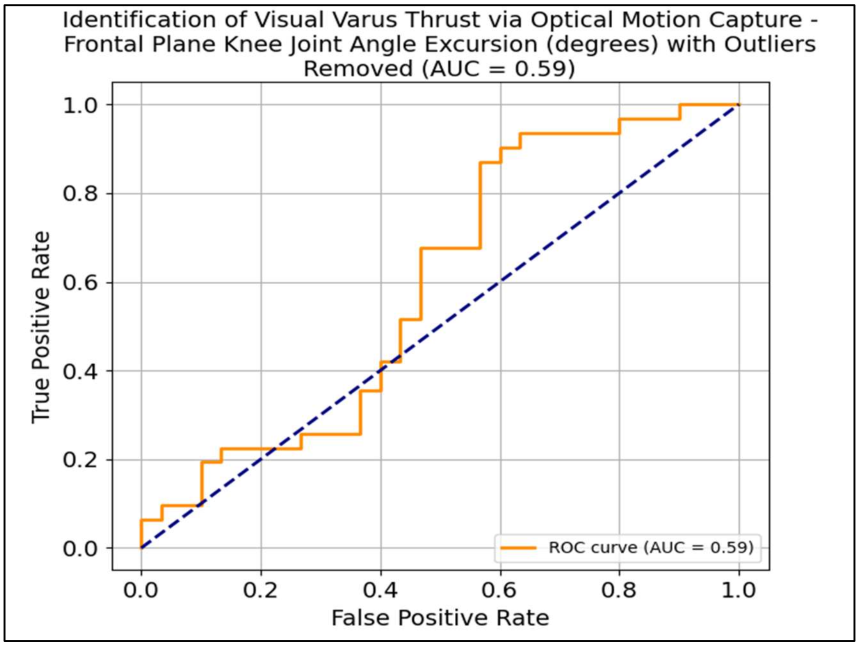

Figure A3: The ROC curve illustrates the diagnostic performance of the optical motion capture system in detecting varus thrust, for the full participant pool with outliers removed. The area under the curve (AUC) is 0.59, indicating failure in discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5).

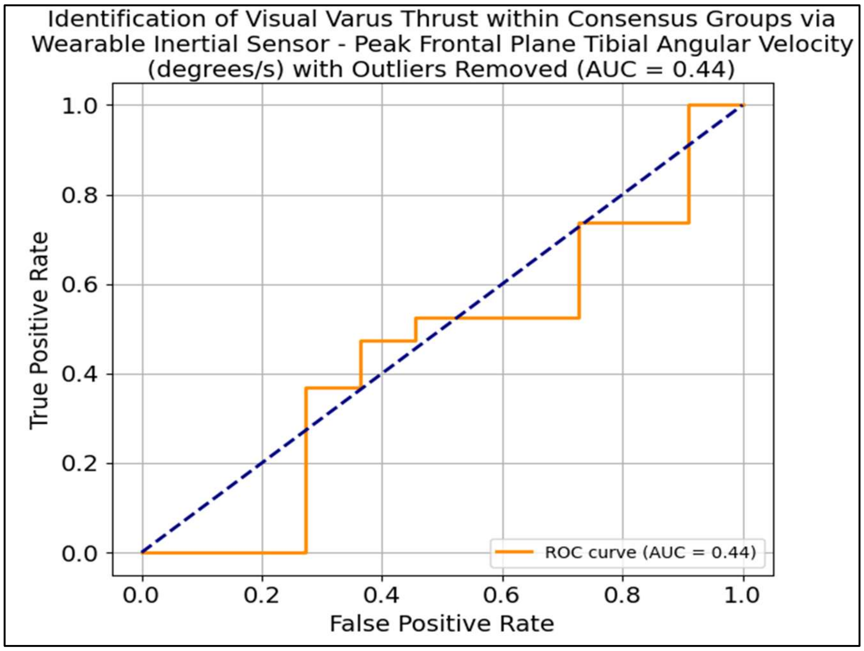

Figure A4: The ROC curve illustrates the diagnostic performance of the wearable sensor system (gyroscope) in detecting varus thrust, for the consensus group with outliers removed. The area under the curve (AUC) is 0.44, indicating failure in discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5)

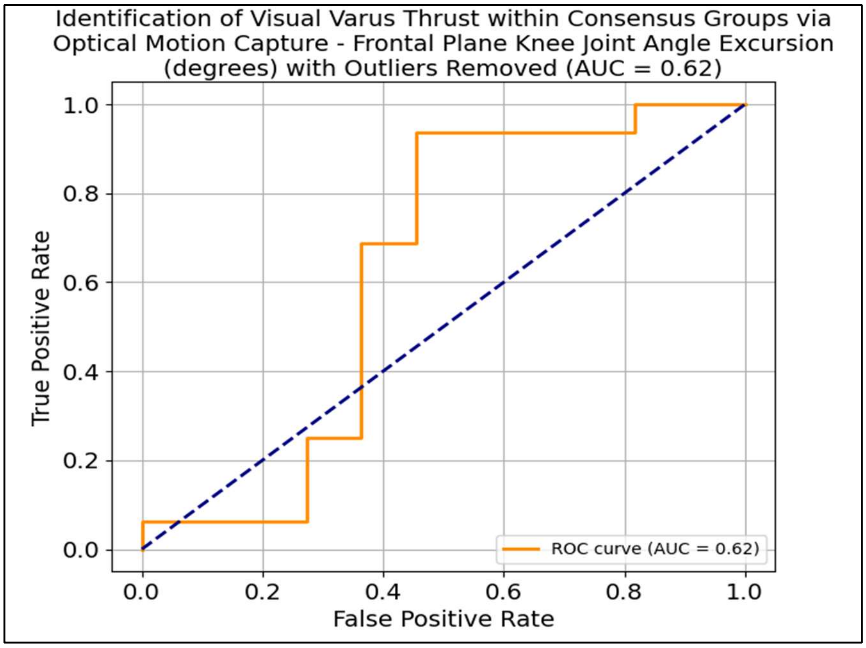

Figure A5: The ROC curve illustrates the diagnostic performance of the optical motion capture system in detecting varus thrust, for the consensus group with outliers removed. The area under the curve (AUC) is 0.62, indicating poor discriminatory ability. The dashed diagonal line represents the line of no discrimination (AUC = 0.5)