APPLICATIONS OF DIGITAL IMAGING CORRELATION TO WOMEN'S KNEES

A Thesis

by

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ABSTRACT

Women are susceptible to knee injuries, like torn ligaments, and diseases such as osteoarthritis and sarcopenia. Researchers in the fields of physical therapy, sports science, and medicine have been investigating topics centered around the complex joint that are tedious, expensive, or lack of accuracy. The present study provides a new engineering technique approach to women's knees that is non-invasive and insightful. The objective of this research is to evaluate a non-invasive method to study the behavior of women's knees.

Digital imaging correlation (DIC) is a high-resolution camera system that calculates deformation in subjects through tracking a pattern applied to the surface. Offering many benefits in comparison to past strain measurement devices, DIC could potentially provide supplemental data to the research surrounding the injury prone knee joint. The scope of this study focuses on the feasibility of utilizing DIC in the biomechanical field and implementing an application process to ensure accurate results on active humans, specifically targeting the knee.

In order to apply DIC on moving knees, a new method was developed to enable quality images. Temporary tattoo paper provided a safe, easy, and quick pattern application to the skin without hindering its natural behavior. A pattern was developed specifically for analyzing a squat like motion in which the field of view, system set up, and curvature of the knee were contributing factors to the development. Two studies used this technique.

The first study hypothesized that performing resistance banded squats would utilize neuromuscular activation for proper control to reduce the knee valgus position of participants knees, which is linked to injury. Displacement data was compared to evaluate the hypothesis.

The second study compared the knee of a mother and daughter duo aged 30 years apart. DIC captured the effects of aging like osteoarthritis, sarcopenia, and loss of elasticity in skin. Overall, DIC captured the skin's movements, which consequently result from the behavior of the variety of tissue underneath the surface.

In concluding, this work proves DIC as feasible and provides a method to accurately apply reliable speckle patterns to the skin of active humans. The technique can be implemented into future studies concerning a variety of fields.

DEDICATION

For my sister who tore her ACL twice, my dad who has had two knee surgeries, and for my mom who footed the insurance bill. Also, for my twin sister for letting me drink the maroon Kool-Aid.

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NOMENCLATURE

DIC	Digital imaging correlation
FOV	Field of view
WD	Working distance
ACL	Anterior cruciate ligament
DPI	Dots per inch
LCL	Lateral collateral ligament

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1. INTRODUCTION

The purpose of this section is to provide background information for both digital imaging correlation (DIC) and the anatomy of the knee. The engineering technology of DIC has potential in understanding the biomechanical system of the knee, and so this study explores its feasibility by evaluating the structure and function of knee joint system. An overview of the history, theory, and applications of DIC are provided. Current research and issues involving the knee joint are also outlined. This section covers reasonings in selecting the knee joint as an area of interest.

1.1 INTRODUCTION TO DIGITAL IMAGING CORRELATION

Digital imaging correlation is a visual, non-contact method to analyze deformations in surfaces. DIC is simple to use, cost effective, extremely accurate due to its calibration process, and provides benefits not seen in manual strain measurement methods [1]. Through tracking pixel defined areas, known as facets or subsets, the system measures surface displacement and develops strain maps [2]. Each facet must be unique so that it can be properly tracked through the stages of deformation and not be mistaken for another region. Surface appearance is vital to reliable tracking and thus numerous studies have specifically scoped out developing effective speckle patterns. This research provides helpful intuition into what makes precise and accurate DIC patterns [3]. DIC systems are highly accurate due to calibration set ups that initialize the spatial region of the equipment, defines optical variables, and focuses the subject under evaluation [4]. Figure 1 shows the equipment in the DIC system; two high-resolution digital cameras are attached to a tripod with an external light source. Test or calibration plates are necessary for the image acquisition procedure. The hardware is connected to computer system so that images can be analyzed using software.

Figure 1: Dantec Dynamics system set up

Research utilizing DIC was being performed in the 1980's in the mechanical engineering department at the University of South Carolina [5]. In the 1980's, digital cameras were not easy to obtain and thus researchers had to convert film into digital images by utilizing scanners. The digital images produced from scanners were then inputted into algorithms to measure 2D displacements [6]. Digital camera technology eventually evolved, as well as computer processors. As the software engineers developed more robust and faster DIC algorithms, researchers began investigating methods to improve specimen-preparation techniques. Eventually in 1998, Correlated Solutions sold the first commercial turnkey 2D and 3D DIC systems .

21st century digital cameras have progressed tremendously, making DIC the modern answer for measuring displacement and strains, as it provides many benefits in comparison to classical devices such as strain gauges and extensometers. First, DIC is non-invasive as it optically tracks and analyzes images. Not compromising a material's structure during tests provides better data. On the contrary, strain gauges must be attached to a subject, which could hinder the material's movement and performance, and could be difficult to apply to bio-materials [7, 8]. Visually tracking displacements not only provides more accurate results but also leaves a subject in its original condition after testing. This is important for prototype testing or single subject experiments in which researchers do not have multiple samples to work with [9]. In industry, DIC can be applied to existing materials to avoid altering a structure. This will save time and money while simultaneously preserving the natural integrity of said structure. Second, DIC provides a full field strain analysis, while strain gauges can only record data from one area at a time [10]. Strain gauges act as a single point measurement device, causing comparable data collection to be very time consuming. In addition, strain gradients that are obtainable in DIC's full field plots consist of crucial data that are not shown in a single strain gauge output. The plots that DIC produces provide a quick and reliable visual to identify high areas of strain that may be missed if the researcher used a strain gauge in that location [11]. DIC data collection versus strain gauge data has been compared and proven DIC as an accurate strain measurement method [10, 12]

1.1.1 HOW IT WORKS

Displacements and strains are all calculated by comparing images before, during, and after deformation. In order for this to happen, the system has to be able to define where the cameras are in space and in respect to each other. These parameters are defined through a calibration process in which the system detects nodal characteristics of a test plate that is positioned in front of both cameras simultaneously, as seen in Figure 2a. Figure 2b illustrates the principle of a two camera set up which is able to produce three-dimensional data, while a single camera system can produce two dimensional data.

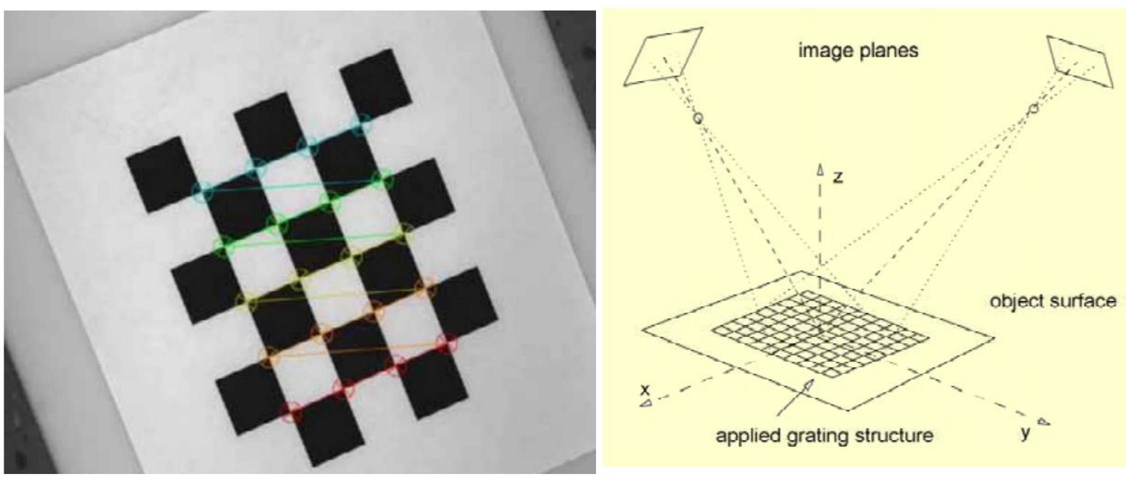

Figure 2. a) Calibration plate with predetermined nodal points b) Principle of 3D image correlation with 2 cameras. Courtesy of Christian Herbst and Karsten Splitthof. Used with permission [4].

After the calibration set up, a series of photos are taken before, during, and after deformation. The software tracks pixel-defined regions throughout the collection of photographs. Displacements are detected in these series of images by a distinct pattern on the subject's surface, typically denoted by an applied speckled pattern. In order for the results to be accurate, the tracking of each region must be reliable. For each region to be tracked true, they must be unique from each other. To better understand the importance of the pattern, it is imperative to understand how the software approaches analysis. As an overview, an illustration of the steps can be seen in Figure 3.

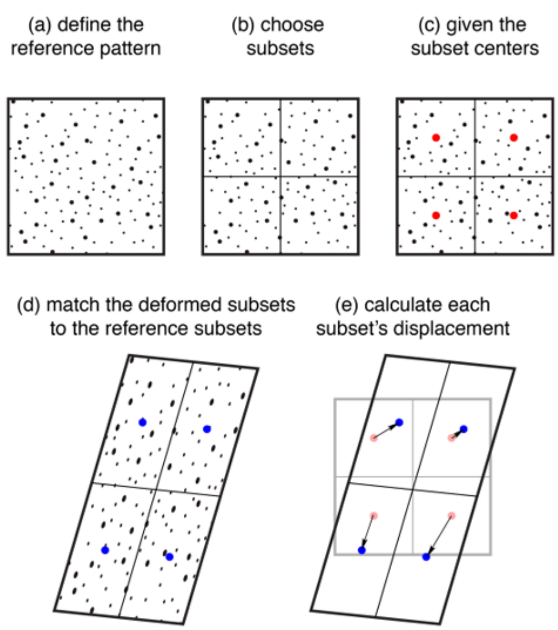

Figure 3. Pattern tracking steps of DIC. Courtesy Will LePage, www.digitalimagecorrelation.org. Used with permission [13].

In more detail, all images are evaluated by the changes in gray vales. This means a speckle is defined by the contrast of its dark border against the white background. Initially, the software will divide the reference step, which is user defined, into equally sized square subsets or facets which the user defines through a select number of pixels, typically between 19-30 pixels. However, a user can choose outside of this range if needed [14]. Determining the optimal size for each subset selection is dependent on the pattern and field of view. Users want each facet to be unique and distinguishable from its neighbor so that the software can distinguish one facet from the next during the tracking between the series of images. To achieve subsets with distinct characteristics, each region needs to have an appropriate amount of speckle. A high density of black speckles could be hard to distinguish and track if that facet becomes skewed during deformation. It could first appear to have a few regions of white, but following deformation, it may appear as a completely black region. On the other hand, a less dense region of speckles could lead to undefined facets. For example, in Figure 4, a good variety in sizes of speckles helps make this pattern trackable through the steps of the DIC analysis. facets.

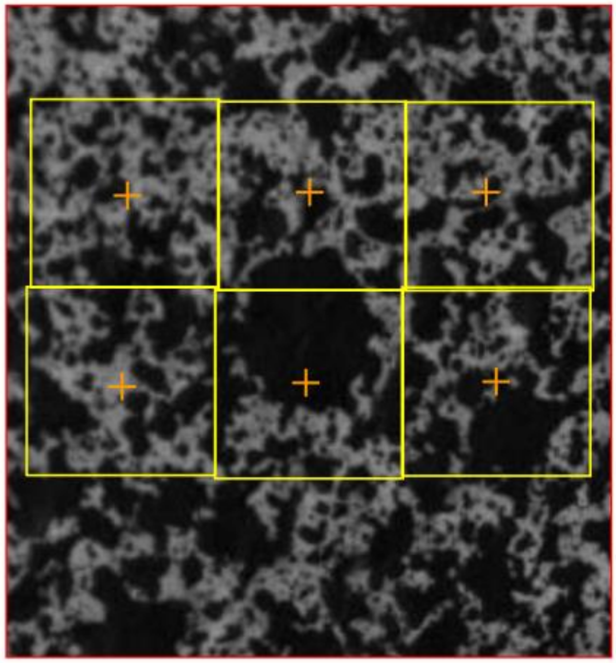

Figure 4. Speckle pattern is divided into facets. The pattern in each facet needs to be unique from its neighbors to be trackable Courtesy of Dantec Dynamics. Used with permission [14].

An ideal target is 6-10 speckles per facet for best results [14]. This helps the user define the pixel size of each subset. Next, the center of each facet is marked in the reference image, and the displacement of this center point is tracked into the subsequent image, during or after deformation. The system must be able to match the pattern in the step image to the reference image to obtain results for that region. This displacement value is then used to calculate the strain.

1.1.2 PATTERN IMPORTANCE

Although some DIC systems can use the bare surface of on object, speckle patterns are in most cases applied for best results. As briefly mentioned above, the pattern is crucial in the system to calculate accurate and reliable data. For the subsets to be distinguishable from its neighbors though, there are a few key features to keep in mind when developing a pattern and can be seen in Figure 5.

- **Random:** The dots inside must be arranged unique in each facet.
- **Isotropic:** Such that the pattern is biased in any one direction.
- **High Contrast:** Because the system first evaluated images using gray scale values, the pattern needs to have a high level of black vs. white with little variation or "gray" in between. In working with oddly shaped objects, shadows and reflections could make a "gray" area seem darker or lighter than it is, adversely impacting the results. Some research uses histograms to rate the contrast value in patterns during the selection process.
- **Scaled Appropriately:** Patterns need to be sized according to the field of view. As the distance between the cameras and subject increase, so should the pattern size. The user defined facet size feature allows for some room for non-perfection. Once in the software, if the pattern seems slightly too large, the subset size can increase. This however is within reason and should not be mistaken for any size fits all mentality.

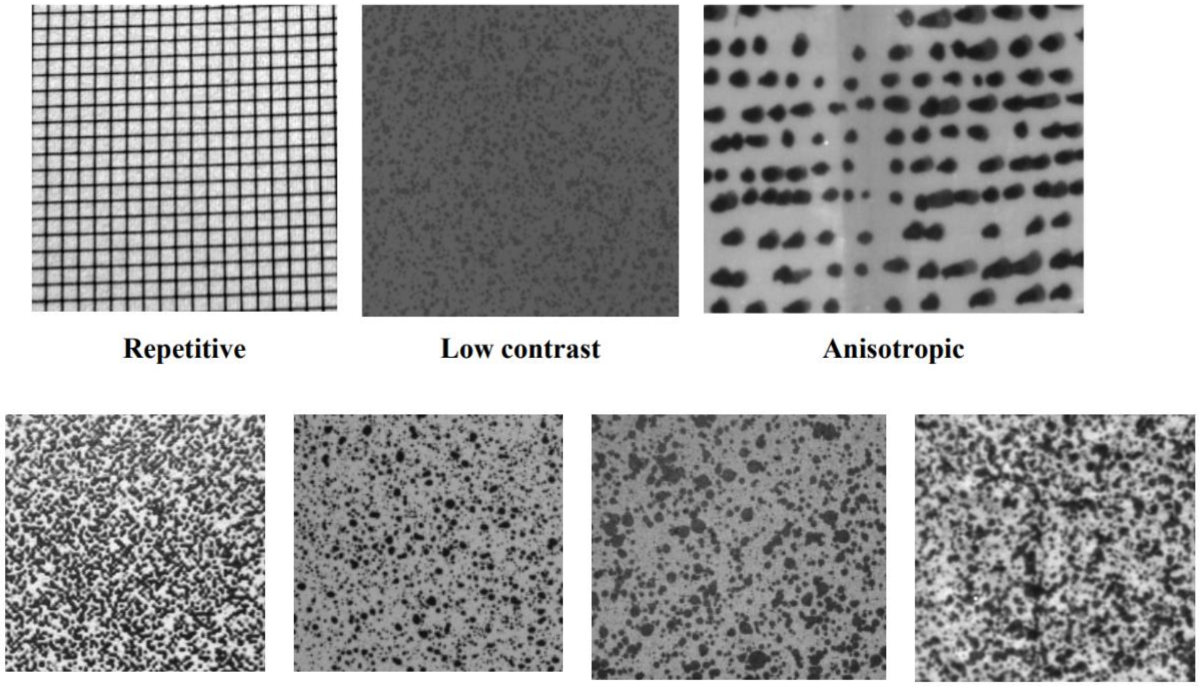

Figure 5. The top series of images show unwanted pattern characteristics. The bottom row illustrates good patterns that show contrast and appropriate distribution. Courtesy of Correlated Solutions. Used with permission [15].

There are many application techniques for patterns. Projecting speckles using a computer and projector is useful in shape identification, but lighting can cause placement to be misconstrued. Hand marking is useful for small areas but is inefficient when dealing with time constraints. Uncertainties vary as each person speckles uniquely. Stenciling works well on larger subjects but stamping the same pattern over and over violates the random rule. However, it works on large areas because the neighboring facets have enough variation. It should be noted that roller stencils and stamps are tough to apply to softer materials. The most popular technique practiced is spray painting. This method utilizes paint to produce random shaped and sized speckles.

Research has been conducted to determine whether a white background with black speckles obtains more accurate results, as compared to a black background with white speckles. However, publications support neither side thus the consensus is that the color order is irrelevant while the contrast and pattern formed are key [16]. Test trials and practice are important to gain experience with this method. Lastly, transfer paper is an application that utilizes printing a pattern and then applying to the subject. This technique, although not as common, is predicted to be useful and therefore is used in this study for multiple reasons later discussed.

1.1.3 APPLICATIONS OF DIGITAL IMAGING CORRELATION

Generally, DIC is used to characterize materials, evaluate structural damage, and ensure quality control in manufacturing. Today, digital imaging correlation is expanding quickly to be used in industry applications. Civil engineering fields utilize DIC by examining structures under specific load conditions [17]. In 2008, over 16,000 bridges were evaluated and categorized as structurally deficient or functionally obsolete, which resulted in over $130 billion in repairs and replacements [18]. However, some experimental assessments can reclassify bridges to have a more accurate safety rating, thus avoiding meaningless expenses. Traditionally, measurement devices are limited to assessing bridges as they are time consuming, costly, and risky depending on the accessibility of the bridge [6]. DIC can be used to analyze these large structures and provide a quicker and safer option compared to strain gauges. A set up of data collection can be seen in Figure 6.

Figure 6. DIC assessment of bridge courtesy of Dantec Dynamics. Used with permission [18].

The National Physical Laboratory is working to apply DIC on in-situ measurements for material characterization and monitoring of engineering components [2]. The system provides validation of finite element predictions as well as strain states that will evaluate a product in the research and design phase. For example, the development of a tire utilizes DIC data during different deformation states. These are complex problems to measure without the DIC technique. Traditionally, this method is used in the realm of materials to help characterize properties, identify strain spots, and generally serve as a full field analysis. As the material category broadens to the biological world, DIC showcases its huge potential as it has the ability to measure a variety of biological tissue.

1.1.4 APPLICATION OF DIGITIAL IMAGING CORRELATION IN BIOMECHANICS

Understanding the behavior of biological materials is important to diagnose diseases, explore surgical techniques, design new biomaterials, and has a whole host of other applications [19]. As previously mentioned, DIC is an efficient means of replacing thousands of extensometers or strain gauges. Non-contact measurement techniques minimally affect the object's natural motion, which is important to consider when working with soft, anisotropic materials such as human tissue. Applying strain gauges to a person's muscles produces a new set of challenges and occasionally hinders the natural motion that the tissue would typically have. Also, strain gauges are limited in that they cannot measure motion outside of the plane. Lastly, another benefit of DIC is that rigid body motion can be removed in measurements to active participants. This is a key advantage in measuring human movements as often people rigidly move in their typical motion. In conclusion, DIC allows for a full field measurement to be taken in seconds and easily identifies local strains that could lead to cracking in materials or stress spots. Clearly, biological materials are unique to each person; skin, muscles, joints and the body all grow, behave, perform and age differently. Research in the medical field has provided useful data to help categorize a patient's body based off demographics. However, DIC can provide patient specific values that could improve surgery, training, and the overall experience for patients. Again, preparing subjects for DIC analysis can be relatively straight forward and DIC can handle complex geometries unlike past manual measurement techniques. The human anatomy is far from simple in shape as it exhibits substantial amounts of curves, angles and odd shaped surfaces. Thus, analysis of the human body would require a system that can handle intricately shaped figures.

The next section transitions out of the engineering world and into the realm of the medical field to provide sufficient background information to supplement the decisions made during the study.

DIC systems have been used on soft and hard cadaver materials regardless of the behavior of the subject, i.e. brittle/ductile, isotropic/anisotropic, homogeneous/inhomogeneous [8]. Large and small displacements have been successfully observed with DIC and therefore proves its versatility. It has been used in applications ranging from the microscopic scale, such as small size tissue samples, all the way to a macro scale with organ and bone sized specimens. Studies of evaluating biological materials have ranged from artery tissues [19-21], pig particular cartilage and rabbit inferior vessel tissue [1], to bovine, mouse and human bone samples [22-24]. In the following content, some of these past published works will be reviewed to give an understanding of biomechanical applications, identify triumphs, and also point out some limitations that will serve as motivation for this study.

Some research utilized artificial or animal tissue as a way to apply DIC to the biology field. However, there are many studies that utilize human materials. In one research publication, surgical techniques were analyzed for a fixation method on a "T-type" pelvic fracture [24]. The procedure with the smallest movements during a loading simulation was deemed optimal given that a broken hip cannot move to be healed properly. Cadavers were painted white and speckled black. As a conclusion DIC proved to be an effective technique as it was able to able to tackle a complex shaped bone, detect small movements, and proved to be versatile as the researchers were able to create virtual gauges that measured data along specific fracture points. Clearly, DIC was implemented into the medical field and proved to be an asset in evaluating surgical approaches.

On the other side of the spectrum, DIC can be applied to soft tissue as well. DIC analysis of Achilles tendons showed 3D strain analysis on 6 fresh frozen human specimens that were deformed using a custom-made rig system [11]. To summarize the methods, after the specimens were defrosted they were dyed with Methylene blue and then speckled with a matte water-based white paint applied with an airbrush. Statistical analysis showed that the overall scatter remained below 0.3% and that the linear variable differential transformers showed excellent linear agreement in all the specimens. This report indicates DIC is an accurate measurement for strain on human tendons, which is an inhomogeneous material to analyze.

The past two studies looked at cadavers as a material source, but digital imaging correlation is not limited to biological materials from the deceased. Quantifying strain on skin during living human movements could provide information that will be valuable and more accurate. A study examined the soft tissue of the face by asking one participant to sound out the vowels “AEIOU”, and the strain was captured during these motions [25]. To develop the speckle pattern on the skin, the participant’s face was speckled with black paint using a makeup airbrush. High strain spots were visualized around the eyes and corners of mouth, identifying regions of wrinkles in aging population. This study showed that DIC can be participant specific and capture data from highly curved and soft surfaces. Another publication produced similar results by identifying localized strain on soft facial tissue [26]. Results also showed that subjects over 40 years of age had a statistically significant increase in stretch around the mouth. Further application of analyzing soft facial tissue can be utilized by cosmetic surgeons, beauty product performance tracking such as rejuvenation therapies or Botox fillers, visual animation, and other fields.

Table 1 provides an overview of current research utilizing DIC. Both biological and non-bio materials are included. The pattern application method is given along with the specimen. The table is ordered alphabetically by author but it is color-coded to reflect the specimen type: Pink is cadaver materials, orange is non-biomaterial, blue is living human participant skin, and grey is animal material.

Source	Paper Title	Specimen	Pattern Application Method
De Waele, W., et al. (2014)	*Digital image correlation as a tool for three-dimensional strain analysis in human tendon tissue*	Cadaver Achilles tendon	First dyed with methylene blue, airbrush in a matte water-based white paint
Ghaednia, H., et al. (2017)	*Collision measurements using digital image correlation techniques*	Tennis and lacrosse balls	Painted white and speckled with black ink
Hoult, N. A., et al. (2016).	*Measuring Crack Movement in Reinforced Concrete Using Digital Image Correlation: Overview and Application to Shear Slip Measurements.*	Reinforced concrete beams	None, natural surface of concrete was used
Hsu, V. M., et al. (2014)	*Quantified Facial Soft-tissue Strain in Animation Measured by Real-time Dynamic 3-Dimensional Imaging*	Human face	Black and white colored hair spray
Karanika, M., et al. (2016)	*Assessing osteosynthesis techniques for pelvic fractures using Digital Image Correlation.*	Pelvic cadavers	Black and white spray paint
Lionello, G., et al. (2014)	*An effective procedure to create a speckle pattern on biological soft tissue for digital image correlation measurements*	Porcine collateral ligaments	Stained tissue with methylene blue solution to obtain a dark background and airbrushed the surface with paint to create white speckles
Miura, N., et al. (2016)	*Visualizing surface strain distribution of facial skin using stereovision*	Human face	Makeup airbrush with black and white

Table 1. Sample of previous research data that utilized DIC. Colors denote the type of specimen tested.

Source	Paper Title	Specimen	Pattern Application Method
Moser, R. A., et al. (2010)	*3D Digital Imaging Correlation: Applications to Tire Testing*	Car tire	Black and white paint
Nicolella, D. P., et al. (2001)	*Machine vision photogrammetry: a technique for measurement of microstructural strain in cortical bone*	Bovine tibial bone	Sanded surface polished with diamond paste
Salmanpour, A. H. and N. Mojsilovic (2013)	*Application of Digital Image Correlation for strain measurements of large masonry walls*	Masonry wall	First coated with a white paint and then random black speckles were applied
Sztefek, P., et al. (2010)	*Using digital image correlation to determine bone surface strains during loading and after adaptation of the mouse tibia*	Tibiae of male 8 week old mice	First applied thin layer of matt, water-based, white paint and then speckled with matt, water-based, black paint, using a high precision airbrush
Zhang, J., et al. (2005)	*Strain and mechanical behavior measurements of soft tissues with digital speckle method*	Porcine articular cartilage	Sprayed with water-insoluble black paint

Table 1 Continued. Sample of previous research data that utilized DIC. Colors denote the type of specimen tested.

1.2 SELECTION OF KNEE AS AREA OF INTEREST

In evaluating possible anatomical regions to focus on, this research should select a challenging and multicomponent region of the human body. Using this criterion coupled with personal connections, this research will investigate the human knee and its challenging, complex geometry and it is an interesting region since it encompasses multiple bio tissues working together as synched together as seen in Figure 7. It will show skin stretching over a large area in different directions and a multitude of surfaces under the skin, namely, the bone, muscles and tendons that reside beneath the skin. This joint is the epicenter for countless studies as it applies to young athletes with knee injuries, patients with osteoarthritis of all ages, surgical joint replacements, as well as strength and conditioning fields.

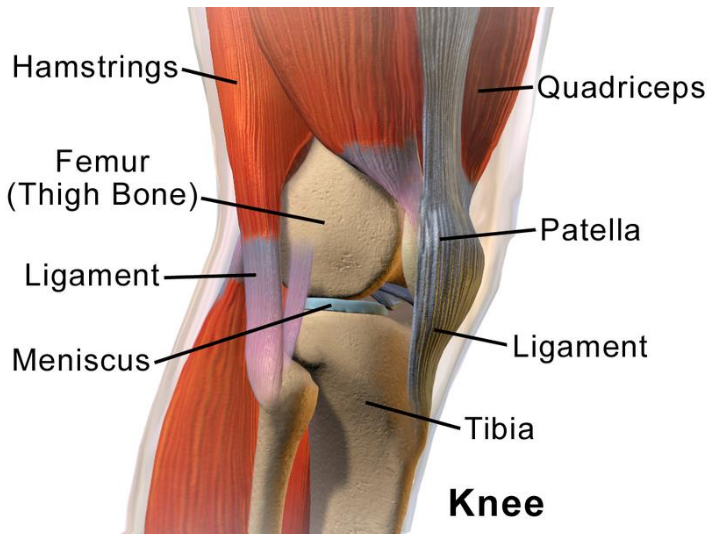

Figure 7. Anatomical view of the human knee courtesy of Bruce Blausen. Used with permission [21].

1.2.1 KNEE INJURIES (ACL)

Since 1972, Federal Title IX has opened up the door for women to participate in more sporting events. The number of female athletes in the US has increased by 990% at the high school level and 545% at the collegiate level since the 1970's. [27] However, with more opportunities to compete comes a rise in athletic injuries, specifically in women's knees. Women's knees are more susceptible to anterior crucial ligament (ACL) injuries compared to their male counterparts [28]. Some activities have shown data that women are up to 8 times more likely to tear their ACL in comparison to men competing in the same field. Contrary to belief, ACL tears are a result of non-contact 70% of the time. This statistic illustrates that athletes often push their bodies past their own limits by putting their muscles, ligaments, and joints in dangerous positions. ACLs tear in a shearing fashion, in which the top part of the leg (femur) and the bottom portion move in opposite direction causing the ligament to twist past its limitations. It is a quick motion that brings the strongest of athletes down quickly. Figure 8 shows the anatomical movements that cause the ACL to tear.

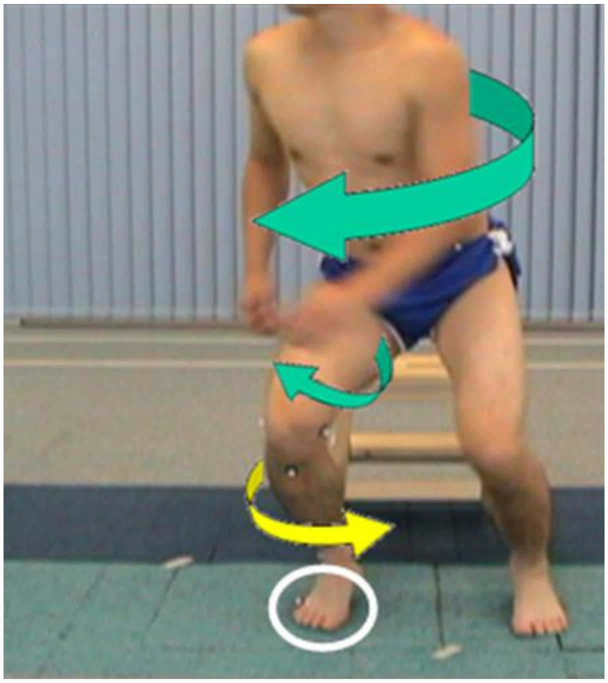

Figure 8. Illustrates the twisting movement that causes ACL injuries. Courtesy of Mak-Ham Lam et al. Used with permission [29].

Common sports where ACL injuries occur are basketball, soccer, and football. These activities all have similar quick motions in common such as cutting, pivoting, jumping, and changing direction or speeds abruptly.

Female athletes are more at risk for ACL injuries for several reasons. Anatomical differences cause instability and imbalance in the muscles of women. A primary reason is the neuromuscular control [30]. Women's gait, or the way they stride out during running and walking, naturally has a valgus tendency in which the knees falls inward during downward motions. Figure 9 shows a female athlete landing from a box jump in which the inward position of the knee is visually seen. This valgus position is extremely common in females during jumping and landing and is a huge contributor in ACL injuries.

Figure 9. During landing, a female athlete tends to have a valgus knee position. A) Two legged jump start position B) Landing from two legged jump C) One legged jump start position D) One legged jump landing position. The valgus, or inward knee, position can be seen in B and D.

This is a natural phenomenon and is a result of the larger “Q” angle that females have. This angle measures the degree connecting the (hip bone) to the patella (knee bone) which follows the quadricep muscle, hence the name. Anatomically, women’s larger hips form larger Q angles, which in turn put more strain and force on the knee resulting in the knee being pushed inward as seen in Figure 10. Valgus knee movement is predominantly evident during one-legged squats and during jumping exercises. These motions apply more force on the knees, explaining the inward collapse typically seen. Physical therapist use these exercises to identify knee strength, help patients retrain their gait to reduce knee injuries, and track improvement during training sessions.

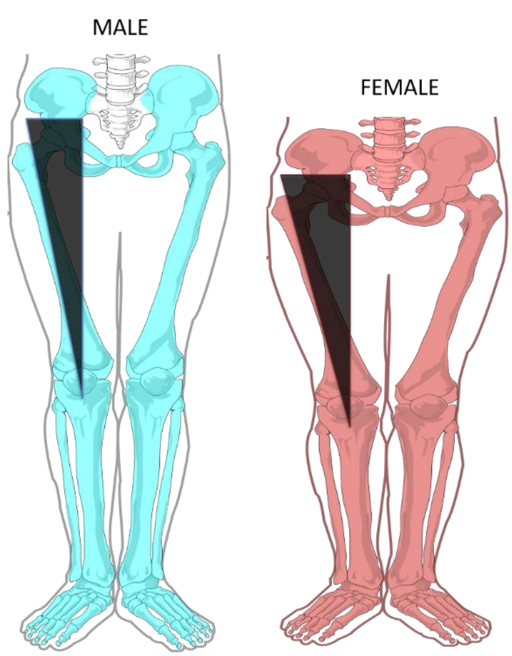

Figure 10. Illustrates the difference in Q angles in male vs. female.

Another main factor of the gender injury inequality is the overall strength and muscle control that women lack in comparison to men. To begin, male ligaments are not only larger but also stronger. As a result, less force is required to tear females' ACLs. Women are considered ligament dominant in which the body uses less muscle to control joints. Stronger, tighter and denser muscle restricts joints from moving outside of the body's limits, thus keeping the knee safe and avoiding injury prone movements. In addition, females squatting motion is quadricep (top leg muscle) dominant. Women do not engage their hamstrings (bottom leg muscle) as much as men do in the downward motion. Using the quadricep muscle as the main operator pulls the knee inward as females' squat, contributing to the valgus positioning. To prevent ACL and other knee injuries, developing stronger muscles and improving on instability is crucial for women.

1.2.2 AGING PROCESS, OSTEOARTHRITIS, AND SARCOPENIA

Although ACL injuries are common in younger adults, other knee conditions can cause injury in older adults. Osteoarthritis (OA) is a common disability in aging adults. Impacting the joints, OA is such a common diagnosis that 30-50% of adults over 65 years old suffer from it [31]. It is considered a wear and tear injury because it occurs when the cartilage protecting the ends of your bones wears down over time. Although several studies have attempted to understand OA, it is a complex disease to define, as radiographic evidence does not represent the amount of pain a person is suffering [32]. Pain is a subjective matter, making it nearly impossible to quantify accurately. In a reported study of 480 adults who reported chronic knee pain, radiographic evidence was only found in about half [33]. Resistance band and muscle strength development routines have been studied to show the effects with participants suffering from OA [31, 34-36]. Because the relationship of pain and deterioration of cartilage do not coincide, perhaps a DIC approach could give more insight to the diagnosing of OA or prevention techniques.

Currently, the recommended approach to evaluate and suggest treatments for OA is the Western Ontario and McMaster Universities (WOMAC) osteoarthritis index [37]. WOMAC is a questionnaire that covers pain, stiffness and functional difficulties for potential OA patients and it can be conducted over the phone [38]. DIC could capture the biomechanics of the knee that would provide a more extensive and quantitative analysis compared to a questionnaire. DIC's data could set benchmarks for age, gender and other demographics.

Cartilage is not the only tissue impacted by the aging process. Sarcopenia refers to the loss of muscle mass due to the age. Proven factors that cause sarcopenia are hormonal changes, decline in activity, illness, bad nutrition, and neurological changes [39]. Loss of muscle mass impacts the quality of life for older adults and therefor preventive measures and techniques to delay the sarcopenia process are currently being investigated. The biomechanical system of the knee heavily relays on the support and control of muscle activity and therefor included in this work.

Lastly, perhaps the most obvious tissue impacted by the aging process is the skin. As the largest organ in the body, the skin protects our internal components and endures extreme amounts of wear and tear of the year. Below in Figure 11 is a photo of the knee joint between two different age group participants. Aging effects are visible noticed in the skin's wrinkles and worn appearance.

Figure 11. Comparative look at aging of skin around the knee joint a) 55-year-old woman b) 24-year-old woman.

2. MOTIVATION AND OBJECTIVES

This section outlines the scope of this work. Aims, objectives and the motivation behind these goals are discussed. A flow chart is provided to illustrate the designed thought process of this work.

2.1 OPPORTUNITY IN PROFESSIONAL SETTINGS

As discussed in Section 1, in reviewing multiple studies there is a common trend of applying a speckle pattern using painting methods [1, 8, 11, 16, 19, 20, 23-26, 40]. Although these were proved successful, the method of application is time consuming. If digital imaging correlation were to be applied in a professional setting, like MRI and x-ray equipment, it is unrealistic to expect doctors, physical therapists, or lab technicians to request painting a patient’s body. Aside from the uncomfortable situation the patient would experience, the operators would waste time in ensuring the pattern would produce accurate results. Painting, much like writing is specific to each hand and therefore inconsistent depending on the subject and the operator. In considering DIC to be a tool outside of a research setting, one goal of this study is to demonstrate a pattern application method that is done in a timely manner and proves to be reliable.

Another goal would be to analyze human motion on live participants. Instead of biological “materials” that were collected from cadavers, this study will focus on obtaining data from live human subjects. This could open the door to other fields such as physical therapy performance tracking and optimal strength and conditioning training. Perhaps a better understanding of skin motion could even apply to plastic surgery and prosthetics.

Computer aided surgery is an up and coming field that DIC can provide patient specific data for. Compared to traditional methods and the high costs of animal subjects, surgical simulations offer training to students at a reduced cost as well as a rehearsal practice for surgeons [41]. Obtaining reliable tissue properties is difficult to achieve when producing a simulation. DIC however can provide patient-specific simulations that will help visualize postoperative appearances and allow surgeons more accurate simulations [42].

2.2 OBJECTIVES

The overall goal of this research is to prove the feasibility using DIC to study the movement of women's knees. To accomplish this, there are two objectives:

- Identifying and developing an easy method to obtain deformed skin patent within a large range.
- Finding effects of the movement of knees on the strain of knee's skin.

This study will provide a method to measure deformation and track movement in the skin. By using tattoo paper, this application technique is reasonable to apply to patients in a professional setting such as physical therapy, strength and conditioning training, computer-aided surgery and other biomedical fields. By proving DIC can be effective on a complex shape such as a knee joint, then the technology can be further developed to accommodate the needs of other anatomical regions. Finally, this study will provide an innovative approach to analyzing knee motion as well as skin behavior.

2.2.1 SPECIFIC AIMS

- Evaluate the feasibility of utilizing DIC as a method to collect data from living humans
- To study the motion of women's knees to gain insightful knowledge that could be useful in understanding injury prevention
- To provide a method of pattern application that is more efficient than painting by utilizing wet transfer paper/tattoo paper
- Study the effects of aging on the skin and prove DIC can be applied on multiple skin types

Experimentally, the following tasks are conducted:

- Analyze speckle patterns at a variety of field of views
- Analyze patterns at different dots per inch scales
- Compare participant skin types through the data given from DIC
- Compare participant motion and movement to gauge neuromuscular activity
- Study skin strain over knee joints, which have a range of biomaterial under the skin's surface

A research flow chart is given to map out the general subjects of this paper and seen in Figure 12. To begin, research focused on the fundamentals of DIC. Next, the biomechanics of the knee was studied, researched and chosen as a region of interest due to large amount of injury and disease associated with this joint. After selection, routines were developed to evaluate the potential DIC could provide in injury and disease prevention. For the studies to be successful, a novel pattern application method must be created. The development phase of the speckle pattern accounted for the range of motion performed by participants, the anatomical curvature of the joint, as well as the application process to the human body.

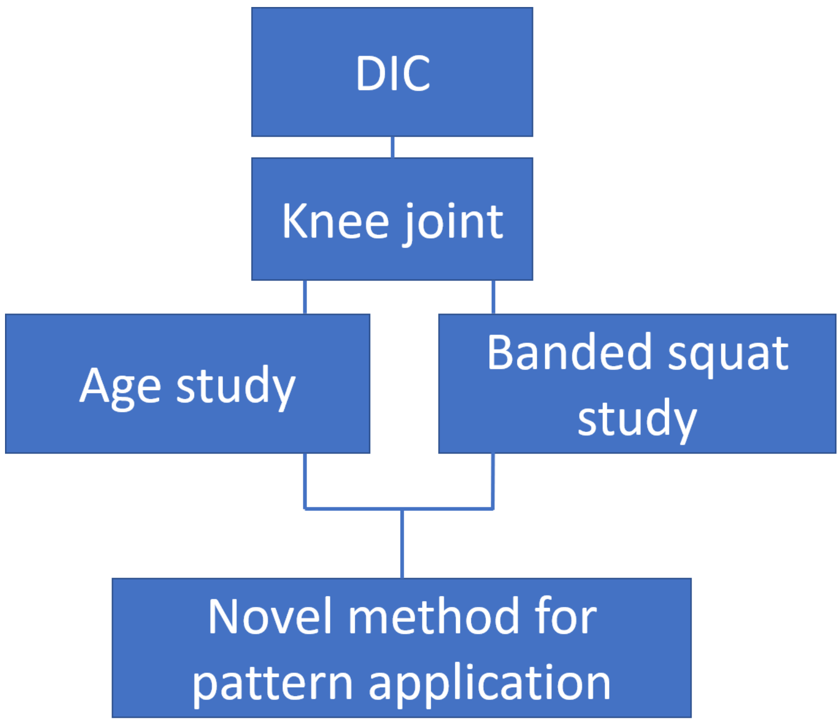

Figure 12. Research overview flow chart

3. MATERIALS AND METHODS

This section discusses the materials, methods, and reasoning behind the decisions made. Temporary tattoo paper was used as an alternative to traditional painting methods as it has potential to be applicable to active humans and is printable. A speckle pattern would be printed onto the tattoo paper medium and applied to the participants' skin. Pattern development was dependent on the field of view, which was determined by the subject matter of the knee and its movement. A rigid body motion test was conducted to determine the uncertainty of the pattern at two different fields of view. An overview of the system set up and selection of participants are also discussed.

3.1 WET TRANSFER PAPER

Recent feedback suggested that multiple prior researchers used a variation of painting as their application technique. Although proven effective in a lab setting, painting is time consuming, usually permanent to subjects, and possibly toxic to human participants, which is why it is unreasonable to paint human subjects repeatedly. In addition, when painting, it is difficult to control the size of speckles and still create a random pattern. This challenge often leads researchers to perform a trial and error based prework, in which they must test out paint, methods of creating a speckle, possibly spray paint or perhaps using an electric toothbrush to splatter paint, and also ensure they are achieving random patterns with the appropriate size speckles. As DIC moves into the realm of biomechanics with living participants, a replacement method of pattern application needs to be considered. Thus, wet transfer paper is a solution that will be analyzed in this work. Wet transfer paper or temporary tattoo paper is less costly, easy to print on, efficient to apply, scalable to specific field of views, and thin enough to not affect the natural behavior of the skin. To meet the objective of applying DIC to active humans, temporary tattoo paper will be applied to participants. This medium will require a speckle pattern to be printed onto the paper. The pattern must meet the criteria as laid out in the introduction.

3.1.1 SILHOUETTE TEMPORARY TATTOO PAPER AND PRINTING PROCESS

Wet transfer paper *Silhouette Temporary Tattoo Paper* was the product of choice as it was easy to find, safe to use, and inexpensive. This method is less toxic in comparison to some paint products and only potential hazard is listed as minor skin irritation [43]. This product can be found online or at craft and hobby stores. It measures 11 x 0.1 x 8.5 inches, and the package comes with two printable sheets and can be seen in the Figure 13a [44]. The weight of the paper is comparable to cardstock, sturdy enough to avoid deterioration in the water application process but pliable enough to feed through a home printer. The printable side of the paper appears shiny and only becomes tacky when dampened with water. A clear protective sheet is layered on top after printing so that the pattern is not ruined and can be seen in the Figure 13b.

Figure 13. A) Silhouette tattoo paper in its packaging. B) Plastic film being pulled back after printing.

The product will work with both inkjet and laser printers, making it very user friendly and adaptable. However, laser printers are known to handle small fonts and fine lines better than inkjet printers. They produce perfect, sharp prints congruent with what is needed in this study. Because of this, laser printers were initially chosen to print the finely detailed and highly contrasted speckle patterns [45]. Nonetheless, issues occurred in the printing process with some lasers printers due to the high heat generated from these machines. The adhesive properties of the paper became melted in several spots causing the pattern to smear and become unreadable. As a result, this study utilized a *Brother MCF-L6900DW*; the paper printing quality was clear, it presented a very contrasting image and did not compromise the adhesive properties of the paper [46]. After printing, a clear protective film is placed over the sheet to ensure the pattern is not damaged during transport and storage.

To apply, the user simply removes the plastic protector sheet, places the pattern on skin with the printed side down, and applies pressure with a damp cloth to release the adhesive printed pattern onto the skin. When the back side of the paper slides loose, this is a good indicator that the printed pattern has adhered properly to the skin. Pulling out the dull standard side of the paper too soon can cause the tattoo to bubble or stretch, thus distorting the image.

3.1.2 TATTOO PAPER ON SKIN PERFORMANCE

A benefit of DIC is its ability to capture the natural behavior of the subject. Concerns that the adhering properties of the tattoo paper may restrict the natural movement of skin were raised. So, to verify the assumption that the tattoo paper does not restrict motion of the skin, half of the knee was covered in tattoo paper and referred to as "Tattoo Paper". The other half was hand speckled with a variety of felt tip markers and referred to as "Natural Skin" has it allows the skin to behave normally. The hand pattern was drawn carefully to follow the guidelines of creating a reliable speckle pattern as outlined in the introduction.

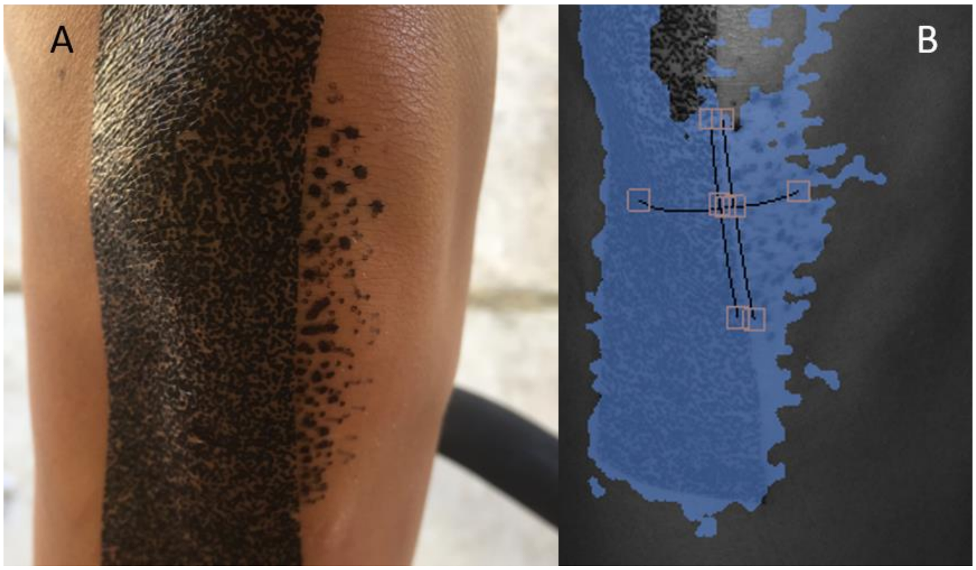

Figure 164. A) Knee with both tattoo paper and hand speckling example. B) Line gauges can be drawn in the software and data specifically from those lines can be extracted. *The blue represents identifiable facets with in the software and is used as a background to show the line gauges.

Two line gauges were drawn vertically and one horizontally as seen in the Figure 14. Constructing gauges is a useful feature of the DIC software. Data from a specific line or point can be extracted during this process. In comparing the movement of the knee, “Line 1” is the gauge on the left side of the knee that gives data for the tattoo paper and “Line 2” is located on the right side of the knee where the skin was hand speckled. Theoretically, the two lines should reflect the same data. A slight variation is understandable due to the lines not being exactly on the same point of skin. Deformation seen occurred from the participant performing a block angle squat. However, the exact motion of the participant is irrelevant because the two patterns are being compared to each other during the same analysis. In examining the data in the below Figure 15 and 16, it can be concluded that the tattoo paper does not hinder the skin’s natural motion. Figure 15 indicates that the movement of each line is following the same trend and values. Figure 16 shows that the horizontal line is symmetrical from the left side to the right, which agrees that the tattoo paper does not alter the skin's properties during motion as a symmetric trend can be observed. Another benefit of DIC is that its non-contact methodology allows its subject to behave naturally. Utilizing wet transfer paper as a means to broaden DIC use into a biomechanical assessment of an active knee does not take away this benefit. Rather, this proves that it can be seriously considered as a pattern technique outside of painting.

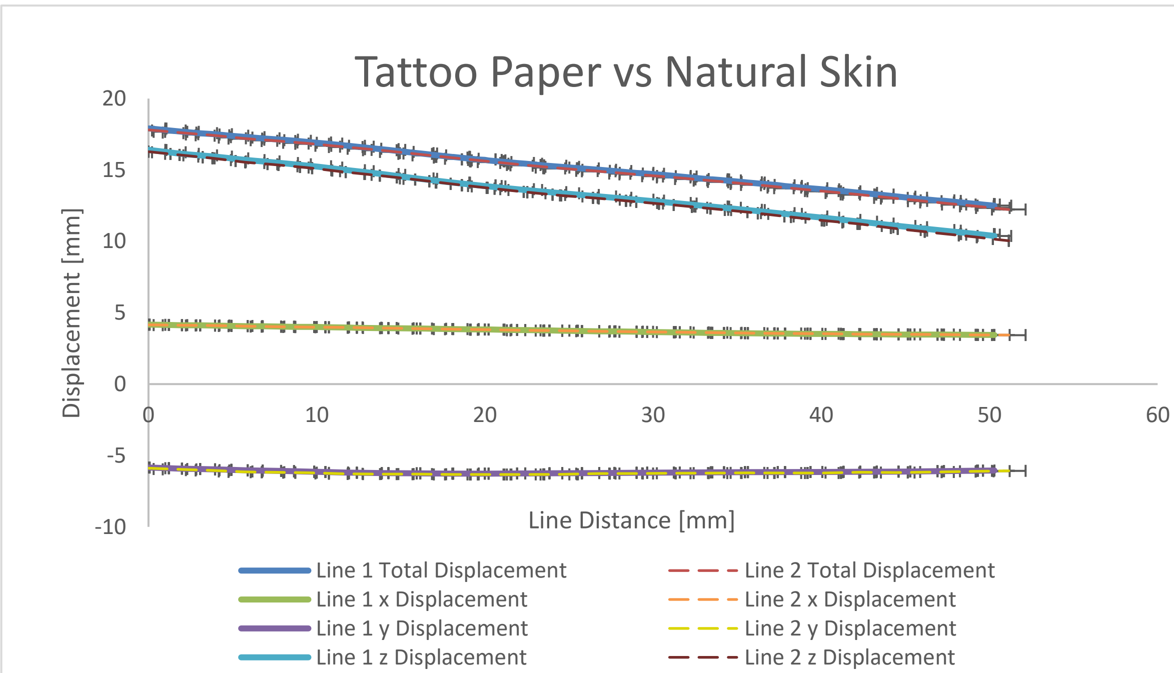

Figure 15. Comparative graph of tattoo paper vs. natural skin using line gauges. Error bars are shown in black and provided from data results.

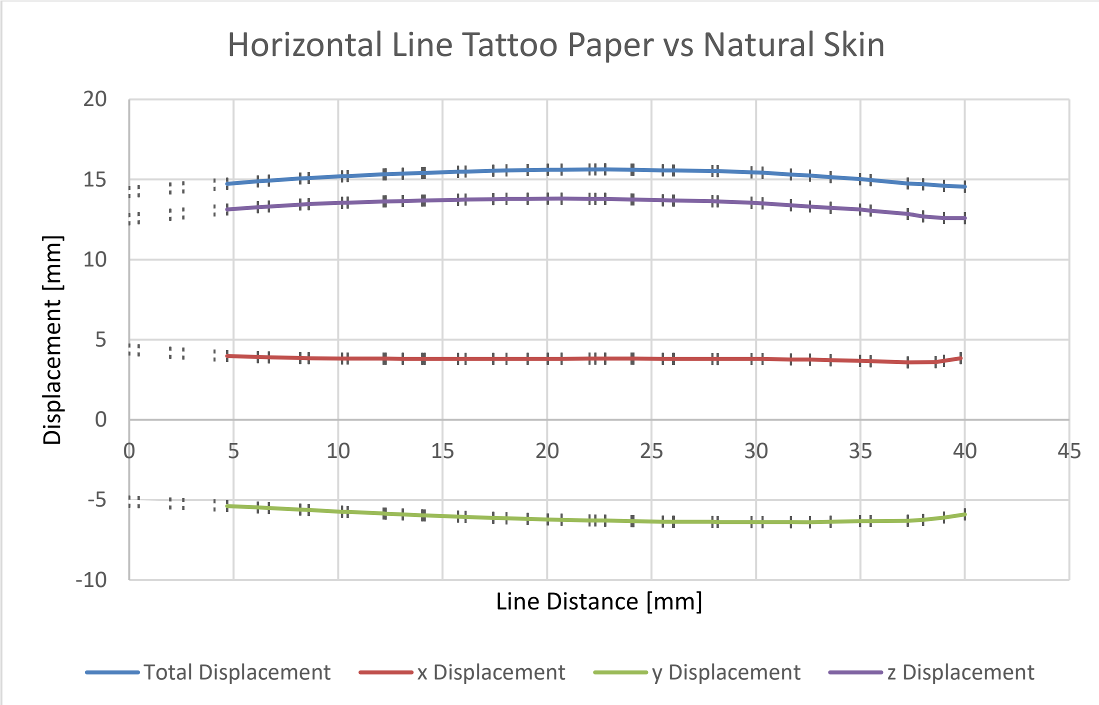

Figure 186. Horizontal line gauge comparing tattoo paper vs. natural skin. Note line points 0-5 give data for the far-right side of the tattoo paper section, which is wider than the given data for the natural skin. These points were removed to help show the symmetry. Error bars in black are provided from the data results.

3.2 PATTERN DEVELOPMENT

The pattern selection for this study underwent several development phases. A pattern was provided by Dantec Dynamics specifically for the 5mpx camera lenses. As previously mentioned, the scale of the pattern is dependent on the field of view (FOV), area captured by the cameras, so the provided pattern was altered by changing the dots per inch (DPI) setting in graphic design, vector editing and illustration software by Corel named *Corel Draw*. It is crucial to use a DPI to alter the size of the pattern so that the number of pixels does not change but the resolution does. After resizing, the image was converted into a bi-color bitmap so that the highest contrast was obtained. This was an extra step taken and done within the high-quality image editing software. Different DPI documents were tested in the lab and evaluated by looking at the following parameters:

1. **Obtainable results**: The system produces data only if the software can track the facets for each step in the series.
2. **Valid results**: The data must reasonably reflect the motion of the knee.
3. **Speckle density:** Since the software tracks facets based on their uniqueness, the number of speckles in each facet is crucial in obtaining results. Each DPI pattern was carefully investigated by evaluating speckle density of subsets.

3.2.2 SCALING THE PATTERN

The pattern must be scaled appropriately so that each subset is distinguishable. Figure 17 and Figure 18 show a range of DPI settings in two different FOVs, with a variety of facet size selections. Recall, FOV is the observable area captured by the cameras. Working distance (WD) is the distance from the camera to the focus plane in which the subject is located at. At a WD of 60cm, the patterns 175-100 DPI are too large, so the 200 DPI setting is more appropriate. The subset sized 29 pixels look to be a better fit as one square does not appear to be as clustered in comparison to the 25 pixels facets.

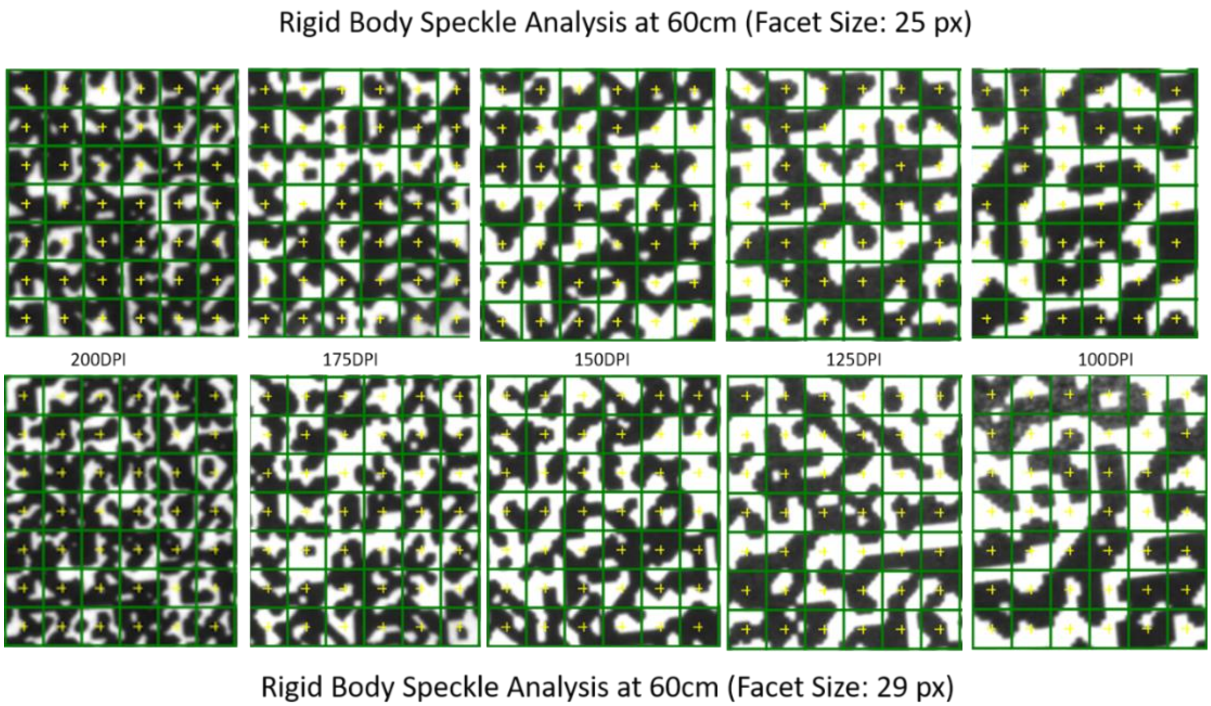

Figure 17. Rigid Body Speckle Analysis for a working distance of 60cm. Top row shows a 25-pixel facet size and the bottom row shows a 29pixel facet space.

Looking at a squat motion of the knee, it was determined the system should be positioned a WD of 100cm away from participants to fully capture the motion of the knee moving in the frame. Figure 18 shows a comparable analysis throughout the suggested definable facet size pixel range [14]. It is clearly evident that the 125 and 100 DPI patterns are too large. The 200 DPI pattern appears too clustered at the 19 and 25-pixel settings. Consequently, experimental test runs using the 175 and 150 DPI were used on active participants to narrow down the selection process to the 19 and 25-pixel settings. Thus, experimental test runs using the 175 and 150 DPI were used on active participants to narrow down the selection process.

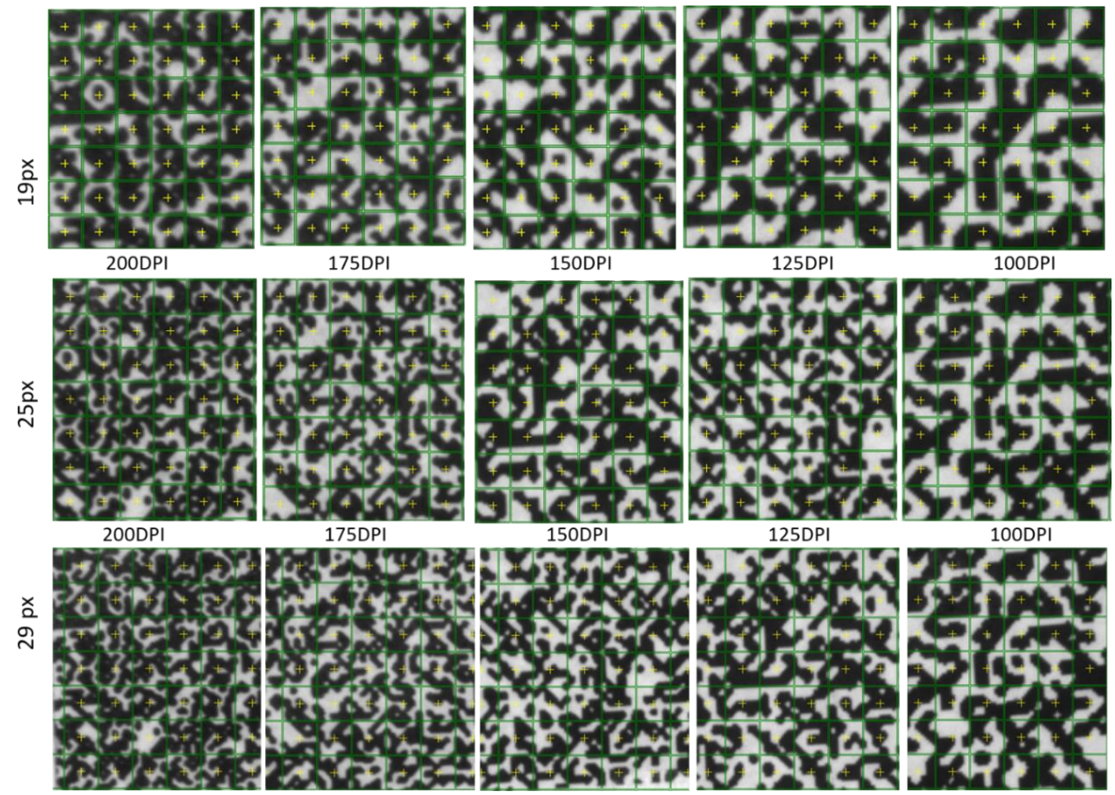

Figure 18. Speckle analysis at a working distance of 100cm**.**

The curvature of the knee provided an optically challenging area to view. As the knee sharply curves from the central forward position, the perspective of the pattern is skewed causing the facets to appear full of speckles. The software will have read this as having a facet primarily black with few distinct characteristics. To compare the assorted sizes, the 175 DPI pattern was applied to the left of the knee and the right side had a 150 DPI sized pattern as seen in Figure 18. It was important to split the knee symmetrically up and down to ensure each pattern would experience similar behavior. By symmetrically splitting the patterns, the top, middle and bottom region of the knee will be evaluated at both DPI sizes. Thus, both patterns will experience the sharp curvature backward that is characteristic of the knee’s surface.

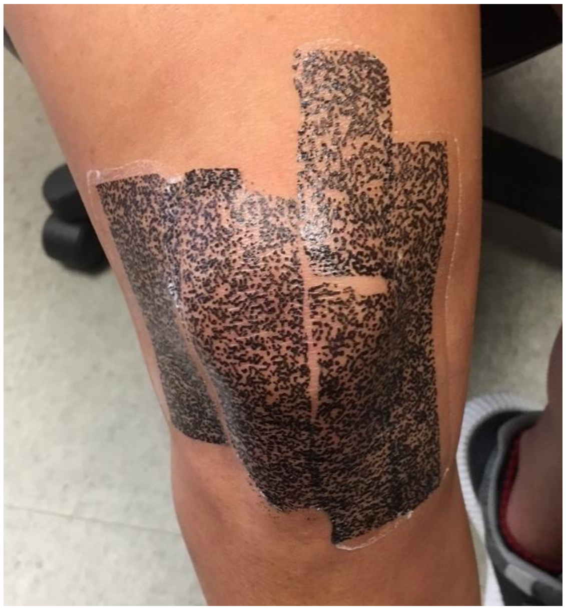

Figure 19. Experimental pattern analysis where the left portion of the knee was patterned using a 175 DPI scale and the right side using a 150 DPI scale.

The further lab investigations concluded that the top portion of the knee needed a higher DPI pattern in comparison to the lower portion of the knee. This is evident in the Figure 20, which evaluates each pattern scale at different knee regions. The bottom portion of the knee is too clustered with speckles at the 175 DPI setting, leading to the assumption that a 150 DPI setting is more appropriate for this drastic knee curvature and sharply angled perspective. The top part of the knee requires a 175 DPI pattern, as the smaller DPI setting is too large of a pattern that each facet does not contain 6-10 speckles. There is a need to combine both sized patterns. This is due to the downward angle in which the camera captured the knee as well as to the complex geometry of the anatomical region itself.

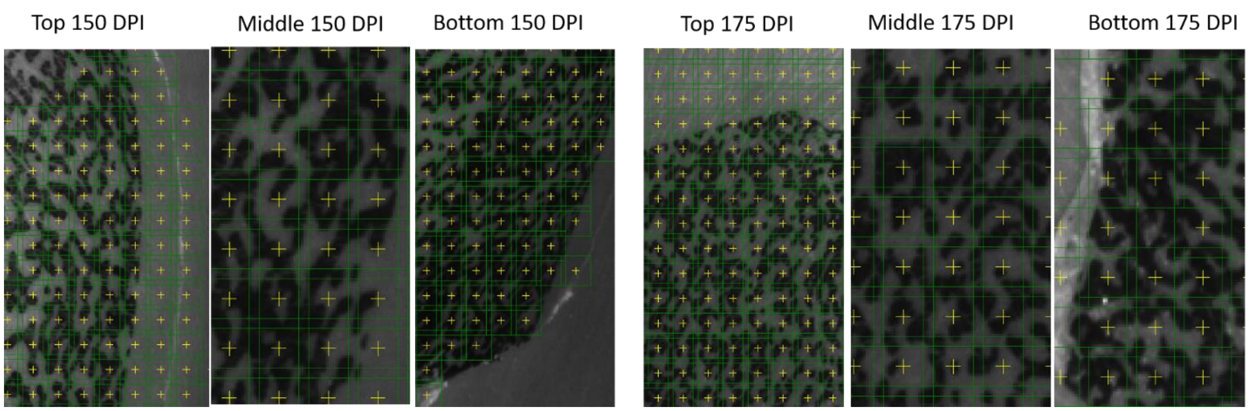

Figure 20. Experimental close investigation of different scaled patterns. The facet size was defined to be 25 pixels. The working distance was 100 cm.

3.2.3 UNCERTAINTY IN THE PATTERN

A range of scaled patterns were printed and placed next to each other to create a sample subject to investigate. The sample subject underwent two rigid body analyses; one occurred at WD of 60 cm while the second was set to 100 cm. The reference image was taken, and then the patterned sample subject was moved about 1 cm for the step 1 image. Using the rigid body movement removal feature (RBMR) each DPI setting can be characterized. For the RBMR feature, the Instra 4D software will calculate a rigid body movement of the object between the reference and actual step and subtract this from the measured displacement [47]. Theoretically, the RBMR total displacement value should output to zero because the sample subject did not stretch or shrink but simply translated in motion. Figure 21 and Figure 22 showcase the results.

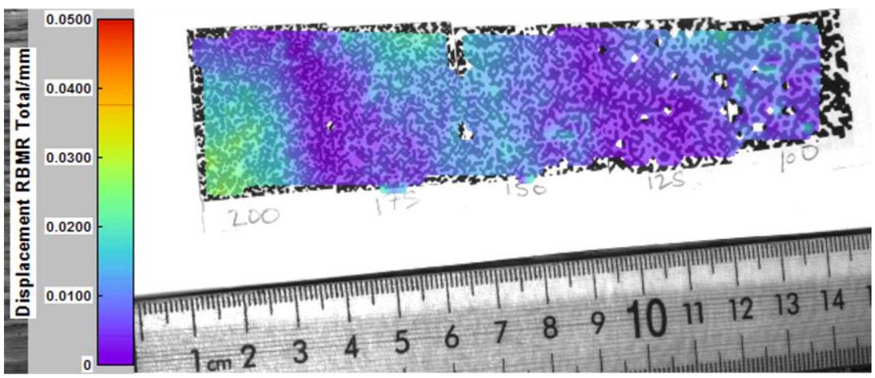

Figure 21. Rigid body test results at a working distance of 60cm. (Results are given in mm).

The WD of 60cm test could not pick up the entire speckle pattern, as the border of the sample subject does not provide the data. This is perhaps due to the fact the patterns are too large and the thus each subset is too crowded with speckles making it entirely too difficult to track. The WD of 60 cm rigid body experiment also shows a great deal in variation, not only through the range of patterns but also in each pattern subject itself. These results conclude that none of the DPI settings are appropriate for a WD of 60cm setup. Conversely, the WD of 100cm rigid body test produced accurate results given the speckled region was able to produce data. Note, outside the speckle region should not be considered as reliable results due to the computer software mistakenly capturing the pencil labels or shadows casting on the sample subject for data.

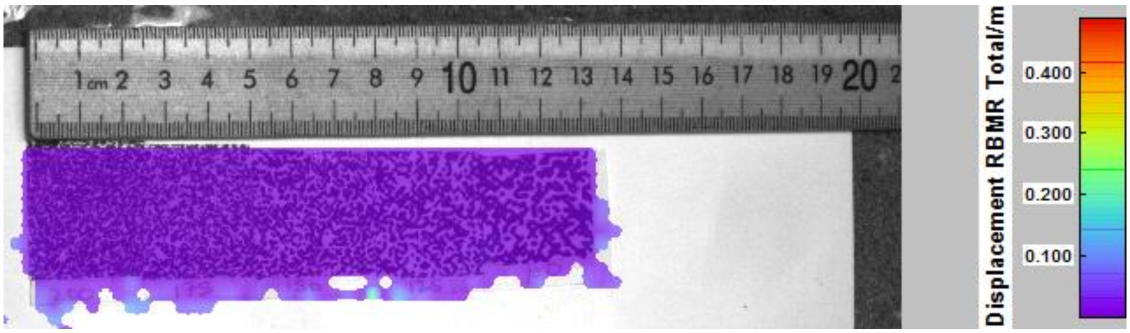

Figure 22. Rigid body test results at a working distance of 100cm. (Results are given in mm)

3.2 SYSTEM SET UP

A two-camera system (5mpx) set up from Dantec Dynamics can be seen in Figure 23. The cameras are positioned on a tripod and connected to a DAQ and laptop with Instra 4D software. The cameras can be repositioned as needed along the rod in which they are attached. The horizontal and vertical angle as well as the tripod height can be altered as well. An external LED light source was used to enhance the photo quality. This did amplify reflective spots on the curved surface of the knee and improved the overall appearance and contrast of the samples.

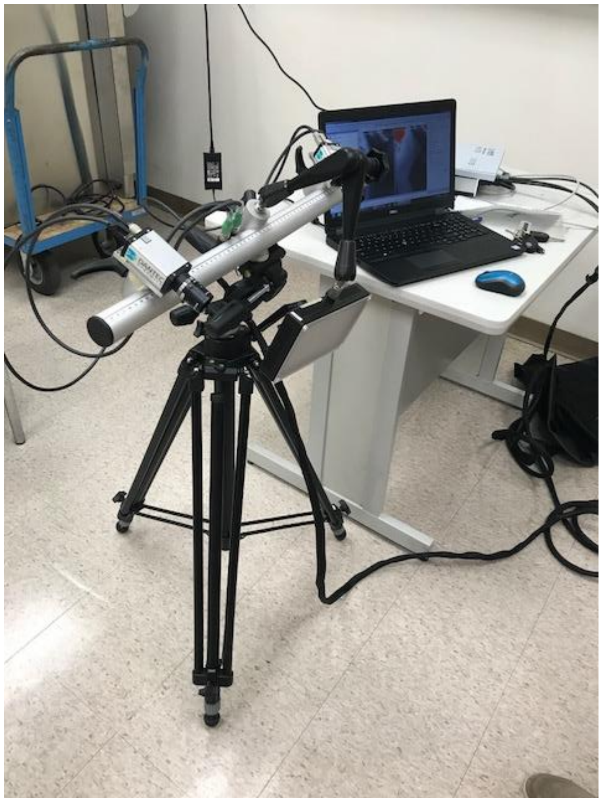

Figure 23. DIC equipment set up

3.2.1 SKIN PREPARATION

After the printing process of the speckle pattern, the paper adheres to the skin quickly and easily. It is important that participants do not have any lotions or natural oils present as this can cause the tattoo paper to ripple up and not stick ideally. After cleaning the knee with water, the pattern was applied by removing the protective plastic film, placing the pattern on the knee while straightened and pressing a wet cloth on the backside until the pattern was adhered. The process takes approximately 10-30 seconds.

3.3 DATA COLLECTION AND PARTICPANT ROLES

Participants were asked to partake in this study if they were female, lived an active lifestyle and could perform the necessary moves. Males are excluded from this study as previous research has indicated women are 7-8 times more likely to suffer from a knee injury. Women's anatomy, muscle composition and hormones all contribute to the susceptibility in knee joint injuries and this is why only females were chosen to look at.

Two studies were conducted in this work. Only four participants were used, as this work investigates the feasibility of the DIC system. DIC produces subject specific data so a small test field of participants for this study is appropriate given the proof of concept aim. A participant overview is given in Table 2. The first study compares two 20-year-old females' knee motion during a reverse squat motion. The purpose is to evaluate if DIC's ability to identify valgus knee trend that is previously mentioned. In addition, DIC's technique will investigate the ideal of neuromuscular activation, which will be discussed more in depth in Section 4. This study tests DIC's potential in the strength and conditioning and physical therapy fields. Study number two examines the aging process in a comparative study that looks at knees of females aged 30 years apart. The purpose of this study will be to determine if DIC is applicable to aged skin. The aging process effects joints, ligaments, muscles and other tissues that DIC's data of the skin's behavior could be telling into what is beneath the surface. DIC could provide supplementary data for research fields investigating skin elasticity for the cosmetic field, as well as identifying the phases of tissue deterioration for sarcopenia or osteoarthritis.

Participant	Study	Age [yr]	Q Angle [°]	Dominant Leg
A	Aging skin	55	16.0°	Right
B	Aging skin	24	16.0°	Right
C	Banded squats	20	15.5°	Right
D	Banded squats	20	15.5°	Right

Table 2. Overview of participants for studies.

Regardless of which study, the following protocol was used for all. First, participants were told what movements they would perform and the application steps of the temporary tattoo paper and all verbally consented. For characterization purposes, a Q-angle photo was taken. The patella, or knee bone, was marked with a bright sticker dot as well as the anterior superior iliac spine, or hipbone. In photo editing software, the angle was measured by drawing a line from the midpoint of the patella to the tibial tubercle, top of the tibia bone, and connecting back upward to the ASIS as seen in the Figure 24.

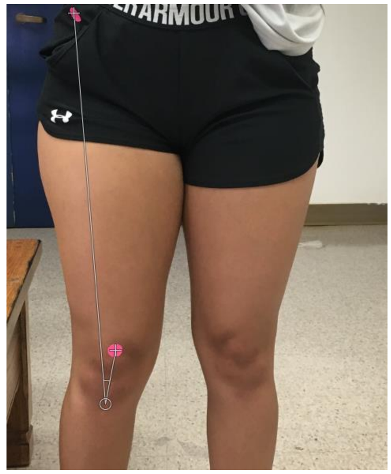

Figure 24. Measuring the Q angle for participants.

After measurement photos were taken, participants were asked the question, “What leg would you kick a ball with?” to determine their dominant leg. The developed pattern was cut into segments and two strips, about 1.5” x 6”, and applied while the leg was in an extended position. Before application the skin needs to be clean and free from any products like lotion, as this will hinder the tattoo paper’s ability to adhere properly. A washable marker was used to mark the center gaps. This will later be used to help redefine the coordinate system in the analysis segment. Subjects remained as still as possible during the correlation set up and calibration process.

During this time, a product called “Spotcheck SKD-S2 Aerosol” was used to minimize the reflective spots on the curved surfaces of the knee. This product is essentially white aerosol chalk and should be used sparingly so that the pattern is not covered up. In the Figure 25 below, the effect of Spotcheck can be seen. The red area represents regions of highly reflective spots. These cannot be identified during analysis and therefore no data will collected at these red areas. After camera set up and calibration, participants were asked to perform a type of squatting motion to deform the knee around the skin. The specific motions will be covered in later sections.

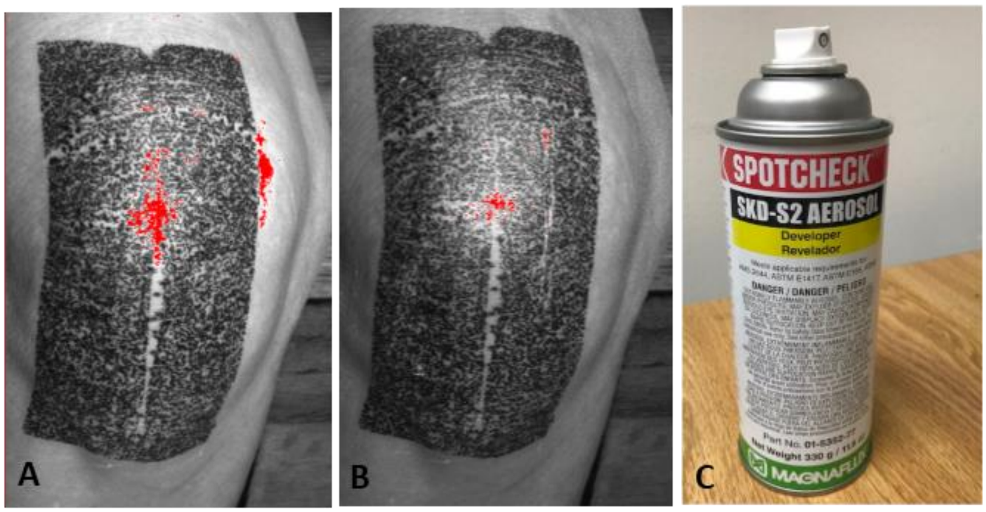

Figure 25. A) Camera view before Spotcheck B) Camera view after Spotcheck C) Product Spotcheck

3.4 SUMMARY

In applying DIC to biomechanics of the knee, temporary tattoo paper was used as an alternative to painting methods used in past research. Temporary tattoo paper is easy to find, safe to use on human skin, and easy to alter to adjust for a specific FOV. This method has a minimal effect on the skin's natural behavior, as proven in a comparative test. Silhouette tattoo paper was the specific product used and the optimal printing method was determined. The DPI scale of the pattern was narrowed down in a rigid body motion test for a FOV of 3 feet away. Preliminary testing indicated that the top portion of the knee and the bottom portion needed different sized scaled patterns to account for the downward angle that the cameras collected data as well as the curvature of the knee. Thus, a combo pattern of 150 DPI and 175 DPI was developed. Female participants were asked to participate in this study for reasons given in Section 1. The developed pattern was applied and equipment set up using the same protocol for each participant and study.

4. BANDED SQUATS STUDY

To understand the feasibility of DIC in evaluating the female knee, Section 4 analyzes two 20-year-old female knee movements while performing a reverse squat motion. Strain and displacement data produced from DIC can potentially benefit the strength and conditioning field as well as the physical therapy fields, as these areas look at mechanics of the skin, muscles and ligaments all working together in a systematic way. DIC captures tissue underneath the surface and therefor can provide visuals as to behavior of biomaterial underneath the skin. This will give trainers, therapists, and other researchers a better understanding into what they cannot see, the movement of muscles, ligaments, tendons and other tissues underneath the visible skin surface. In knowing what tissues are being used, DIC can provide data as to which muscles need to be strengthened, determine the progress of tissue growth, and also evaluate a woman's gait/stride to see if proper muscles and ligament controls are being performed to protect the knee joint.

For this study, a hypothesis was developed stating that a resistance band routine would stimulate neuromuscular activation for proper control to decrease the inward motion known as valgus knee. Valgus knee trends have been linked to high strain rates on the knee, ligament tears and other injuries. Baseline data was collected for a neutral stance and a narrow stance. After baseline, a resistance exercise was performed using a work out band in hopes to activate proper muscles to prevent the knees from a valgus position. After, comparative x displacement field plots were created to look for a valgus knee position. Also, a vertical line gauge was constructed in the analysis portion of the DIC software to measure specific displacement data. The vertical line gauge data was used to assess if the banded squats routine were successful in decreasing the inward position of the knees during a squat motion.

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4.1 ACL PREVENTION AND NEUROMUSCLE ACTIVATION

As mentioned in the introduction, Section 1, women's bodies are biologically built differently which puts them at a higher risk of knee injuries compared to men. This anatomically disadvantage should encourage women to build muscle to compensate for the instabilities of their knee joints. It is not only important to develop muscle strength to protect the ligaments of the knees, but also to train neurological muscle control to activate the correct muscles to reduce risk [48]. Neuromuscles refer to the nervous and muscular system working together. Heavy resistance exercise induces high levels of neuromuscular activation [49]. Essentially, it can be thought of as muscle memory to where a person lifts heavy to actively engaging a muscle. After engaging a specific muscle group, those muscles are activated, consciously working and prepared for the next exercise set. Over a prolonged training period, muscle strengths grows and develops with time [50]. This is the result of the brain telling the nerves which muscles to utilize for a specific motion. Physical therapy, often in rehabilitation, looks to improve or regain optimal neuromuscular functions. They have patients perform specific exercises for targeted areas. Therapists will keep track of the patient's performance on specific notes for evaluation of progress. Outside of rehabilitation, neuromuscular activation techniques are becoming more popular in strength and conditioning fields to become stronger and develop muscle tone, as specific muscles are targeted.

In understanding neuromuscular techniques, the question leads to if muscle memory can help prevent ACL injuries. Can performing neuromuscular exercises before practices or games engage the proper muscles that reduce injury? Can digital imaging correlation identify the neuromuscular activation and track improvements?

Specifically, this study asks whether DIC can identify the valgus knee trend seen in women. Does performing banded squats help activate the proper muscles to lessen the inward motion of knee joints during flexion as this contributes to injuries?

Hypothesis: Participants who perform 3 sets of 20 banded squats will see a decrease in the inward position of knees during a squat like motion. This will be the effect of neuromuscular activation. If proven correct, women will be motivated to incorporate banded squats in pre-work out and warm up routines because having less inward motion correlates to a lower risk of injury.

4.2 PARTICIPANT PROCEDURE

To answer these questions and test the hypothesis, two 20 year-old females underwent a reverse seated squat study, an overview of their physical traits are given in Table 3. Both participants continue to engage in physical training as well as intramural sports. Their activity choices, age and gender put them at risk of knee injuries. Both participants are right leg dominant, so the right knee joint was investigated. Reverse seated squats are performed by starting in a 90° seated position and pushing upward until the participants are in a state of extension and can be seen in Figure 26. Note participants do not need to be hyperextended, locked out knees past the normal range of motion, as this can cause injury [51]. Since hyperextended knees are not a typical or desired position of the joint, the data collection avoided this position.

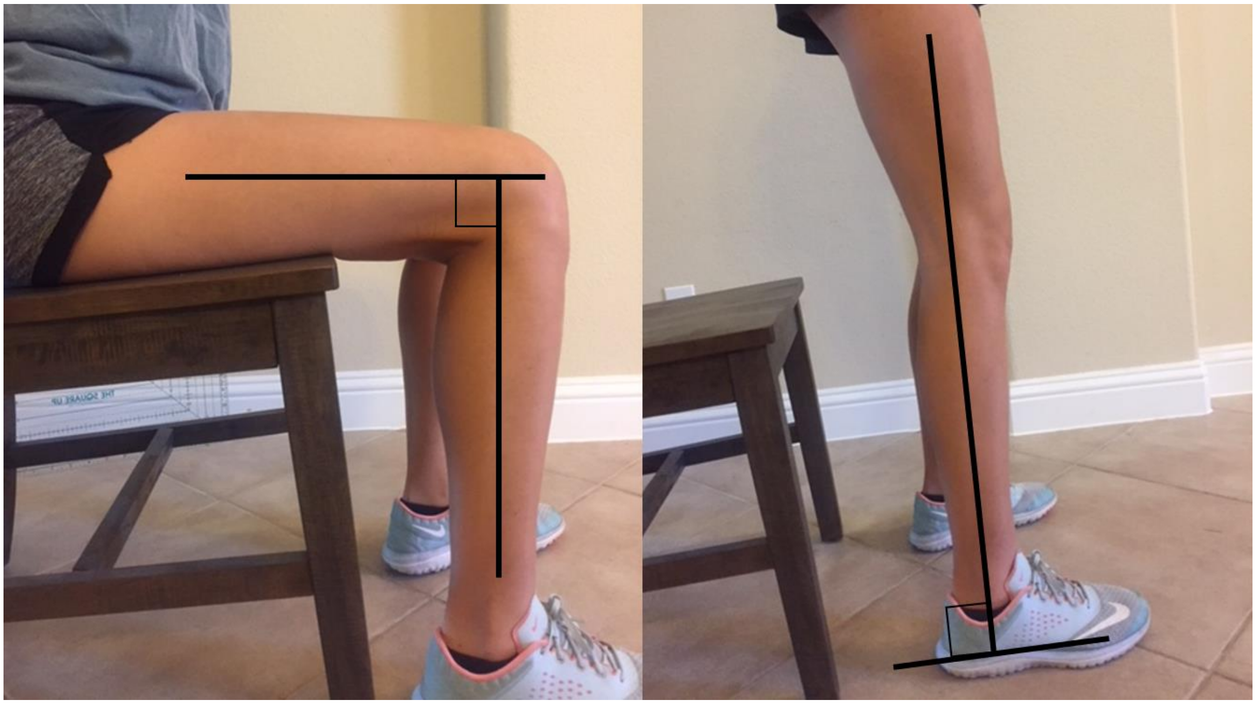

Figure 26. Reverse seated squat example A) Step 0 where participants are seated with a flexion angle of 90 deg. B) Step 1 where participants finish the move in the upright knee extended position.

This movement was chosen as it forces the knees to stay in the coronal or frontal plane. Typically, in traditional squats where the initial position is standing upright, the knee starts over the ankles and transitions forward over the toes as the knee decreases angle into flexion. This motion of the knee joint is too much movement in and out of the coronal plane for the 5mpx camera lenses, so an alternative exercise was selected. Reverse seated squats keep the knee joint placed over roughly over the ankle, as seen in Figure 26, so that the position does not shift out of focus. Reverse seated squats are also utilized in conditioning programs specifically for females' athletes as they engage the hamstring muscle more so than traditional squats, neuromuscular activating proper muscle control. Women power through traditional squats using their quadricep muscles contributing the imbalance that can lead to knee ruptures. The reverse seated squat utilizes neuromuscular activation for proper technique and keeps the knee joint at a rigid point in the FOV so that data collection was achievable.

Participant	Age	Height	Weight	Q angle	Activities
C	20	5'4"	135	15.5°	Healthy/ Athletic Lift weight 3x week Cardio 5x week Intramural sports 1x week
D	20	5'0"	130	15.5°	Healthy/Athletic Lift weight 3x week Cardio 4x week Intramural sports 1x week

Table 3. Physical descriptors of participants. Similar features and activities are observed.

A sturdy long and low table was used to perform this study as it provided a safe base in case participants lost their balance and fell. It also served as a reference marker so that the knee joint was rigid and behaved much like a hinge joint. Concrete blocks were placed underneath participants' feet if needed to adjust for specific heights so that the back of the knee fit comfortably on the ledge of the table. The camera and tripod system was set up at roughly 3 feet away. This FOV was chosen based off the preliminary findings that concurred the distance needed to be able to capture the full movement of the knee during a squat motion. The set up can be seen in Figure 27a below.

Participants warmed up previous to data collection by performing a five-minute light cardio and stretching routine to ensure muscles were engaged and heart rate was active. The stretches were a full body plan, including arms, back, shoulders, and of course legs. Each stretch was held for thirty seconds. Data sets were collected for baseline measurements at a neutral stance, shoulder width apart, and a narrow stance, feet were placed one foot apart.

After data collection, participants were asked to complete a resistance training exercise designed to activate specific muscles. While performing banded squats, a heavy exercise band was placed above the knees and actively pulled legs together, bringing the knees inward, as seen in Figure 27b. Three sets of twenty repetitions banded squats were performed. Here the band is placed around the thighs, close to the knees. A participant would start with legs shoulder width apart and knees extended. Participants would squat down to about a 90° angle of flexion and would rise back up into the starting position for one repetition. The set was performed slowly, smoothly with body control so that muscles were properly engaged. Both participants commented that their legs were tired and could feel their muscles burning. As soon as possible after completion, data sets were collected once again for a neutral and narrow stance reverse seated squat.

Figure 27. A) System set up is seen on the left B) Resistance band being used during squats.

The participants used a *Gold's Gym* blue resistance band, which is the heaviest level band. This most difficult level was chosen as participants are athletic and engage in a weighted work out at least three times a week. These bands come in a package of 3 variety resistance levels, as seen in the below Table 4, and are intended for toning your body while increasing your balance control [52]. Bands are closed looped and dimensions are 16.5" x 4". A knot was tied with in the loop to shorten the size, as the participants' leg stance width was too small for the band. The purpose of the resistance bands is so that body will react by over engaging muscles to compensate for the resistance, hence activating the specific muscles that push your knees outward as the body goes downward into flexion. When performing squats with a resistance band tightly around the legs, the bands force the knees inward and the body naturally reacts by pushing the legs outward. Thus, when the bands are removed, the muscles that were pushing the knees outward are engaged and have the proper activated

Band Color	Resistance level
Blue	Heavy
Red	Medium
Yellow	Light

Table 4. Gold's Gym resistance band color levels

4.3 RESULTS AND DISCUSSION

Before data collection, defining points were marked on the knee so that the coordinate system could be easily definable in the analysis software. The coordinate system was carefully defined as seen in Figure 28a. A 3D model, as seen on in Figure 28b, was also referenced when redefining the coordinate system to ensure that the origin was set in the middle of the knee, at the outermost region in the z-plane. The y-axis vertically splits the knee in half. The split in the pattern is this defining feature.

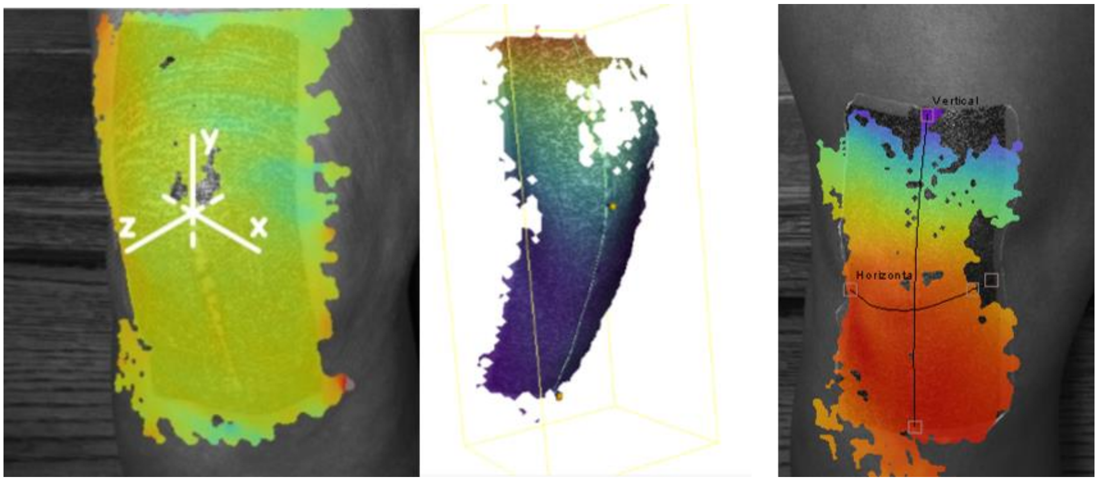

Figure 28. Highlights the capabilities that the Instra 4D software. A) Redefined coordinate system for each participant constructed using defining marks made during the pattern application process is featured on the left. B) A 3D model with a vertical line gauge drawn down the center of the knee for specific data points is seen in the middle. C) A vertical and horizontal line gauge drawn in the software of Intra 4D is seen on the right *Note the figures are provided for visual examples of features of the DIC and therefore the colors that indicate displacement values do not correlate to each other as per default of the software.

4.3.1 VALGUS KNEE TREND CAPTURED BY DIC

DIC's advantage of full field plots provides a visually straightforward process to identify motion and behavior of the joint. Below is a view of participant C's and D's x displacement motion during reverse squats, in which participants begin seated for reference image step 0 and then rise to an upright position in step 1. Note that rigid body motion is included in Figures 29. It was important to examine the rigid body motion as well as the skin stretching to see if the valgus knee trend is captured by DIC. The top portion of the knee, circled in pink, experiences a negative value motion, which translates to the knee moving outward as defined by the coordinate system. In contrast, the bottom region, defined by the white dashed circle, reflects positive values. Thus, the knee is caught in a twisting motion, which is common in females, known as valgus knee, and linked to ACL tears and other knee injuries as previously discussed in Section 1.

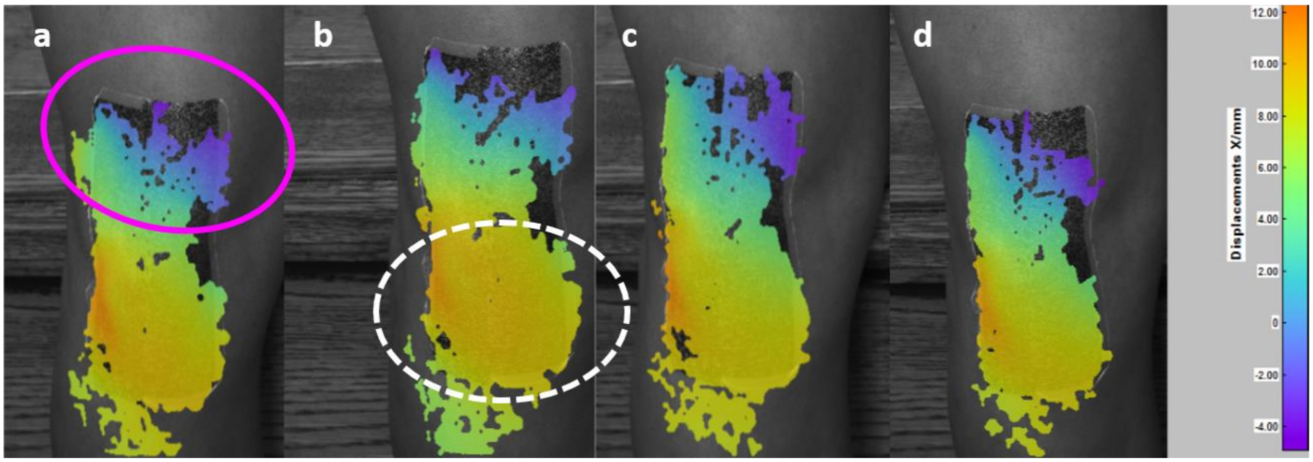

Figure 29. Displacement data for the x direction. A valgus knee trend is captured. a) Participant C baseline neutral b) Participant C baseline narrow c) Participant D baseline neutral d) Participant D baseline narrow. *Note the circles in 3a and 3c denote a region and can be transposed into each photo.

Figure 29 provides evidence that participant C and D both experience a valgus position during the downward motion of a reverse squat. This is concluded by the positive values in bottom sector of the knee (white dash circle region) and negative values in the top sector of the knee (pink circle region). This identification of a valgus knee position is useful for …

- <u>Problem identification</u>: Participants and trainers can visually see the valgus knee trend

- Quantification: A scale or rating, which is standard in physical therapy notes, can be used to define how valgus the knee angle inward
- Problem solution: Trainers and therapist can create an patient specific plan to retrain the participants abnormal gait
- Progress: DIC values can be used to track progress of participant

For this study, since DIC captured a valgus knee trend in these women's knees the study will continue as planned and further explore…

1. The effects of narrow vs. wide stance reverse squats
2. Impacts of performing resistance training with an elastic workout band as a method to activate the proper muscles, to detour valgus knee positions. → Was the hypothesis correct?

4.3.2 LINE GAUGE DATA

To investigate these factors and evaluate the hypothesis, a vertical line gauge was applied to compare the displacements in the x, y, and z direction, as seen in Figure 28c. Directional motions, as defined by the new coordinate system as seen in Figure 28a, were chosen to study reverse squat movements before and after a banded resistance routine because the data includes rigid body motion and the stretching of skin. Both movements together will dictate if banded squats were effective in neuromuscular activation to prevent the knee joint from valgus knee positioning during squats. It will also determine the impact of squat stance width.

Displacement data is calculated for each specific line point drawn on the vertical line gauge. The data is calculated by the change in position from the reference seated photo, step 0, and the final upright knee extended position, step 1. The entire 90° motion was chosen to evaluate instead of incremental angle data sets, as preliminary data, previous research and intuition indicates that the greatest displacement values will be produced between 90° flexion point and the upright extension position of the squat. The scope of this study wants to look at techniques for reducing knee injuries, which occur when the knees move inward with large displacement values. Therefore, incremental angle data values were not considered, as they do not produce max displacement values.

Remember, gaps in the data set were undefined facets caused from the software not being able to identify a unique pattern in that region or by a light reflective spot. In working with a curved surface like the knee, some missing facets are to be expected. Overall, the data appears consistent which indicates successful DIC methods, as eight different data sets were used, and all appear to have similarities.

4.3.2.1 LINE GAUGE DATA X DIRECTION

In evaluating the hypothesis, x displacement data is important to compare baseline and after measurements because the x direction represents the displacement the knee moves inward, aka valgus. The valgus knee was identified as the top region of the knee showed negative values and the bottom of the knee showed positive, resulting in a twisting motion that is closely correlated with ACL tears. Thus, it is important to look not only the values of the x displacement but also the range of the line. A larger range would result in more twisting which is bad for the knee joint.

In the x direction, both participants top portion of knee, roughly 0-25mm on the line gauge, reflect negative values which correlates to the knee rising to an outward position. The bottom region of the knee experiences positive values, thus the knee is twisting as participants perform reverse squats as previously seen in the full field plots. The range of the x displacement values shown on the line gauge is consistently less after banded squats as seen in the flatter line slope for the x direction. This change after the resistance banded squat routine is small but provides potential in affirming the hypothesis.

4.3.2.2 LINE GAUGE DATA Y DIRECTION

Displacement in the y direction data reflects the top region of the knee with the highest values. As the participants rise into the upright position, the top region of the knee experiences the most displacement. This trend gradually decreases and dips into the small negative values. This is reflective the curvature of the knee in the FOV. When the knee curves downward and in, at the bottom of the patella bone, it gives negative y displacement values. In the seated position, this region of curvature appears square to the cameras, but as the limb extends, the curvature of the knee points the facets downward provided negative values. But as the knee extends back forward knee the connecting shin tendon, the values shift toward the zero axis. This meets expectations, as shin size does not change in the y position during flexion and extension, except for a slight movement of the skin, which could occur.

4.3.2.3LINE GAUGE DATA Z DIRECTION

Displacement in the z direction on the vertical line gauge is also important to consider when evaluating the hypothesis, as large displacement values means the knee joint is moving closer to its tolerance. Exceeding tolerance values of displacement in any direction puts the knee in risk of injury. Female knees already experience larger movements compared to men because of their weaker muscles and lax ligaments. Thus, finding a method to control the range of motion will be crucial in lowering injuries.

For the vertical line gauge, the z direction displacement data appears to have the largest values at the top of the pattern. This occurs because the top region of knee begins deep back into the plane from step 0 during the seated position. As the participants stand and perform the reverse squat the upper joint moves significantly forward as the knee extends. The z displacement lines for both participants gradually slope downward to the zero axis, which reflects no movement in and out of the z plane near the shin. Believably so, as this study chose reverse squats for this exact reason; the cameras needed to have a start point in all steps that moved minimally in and out of the plane.

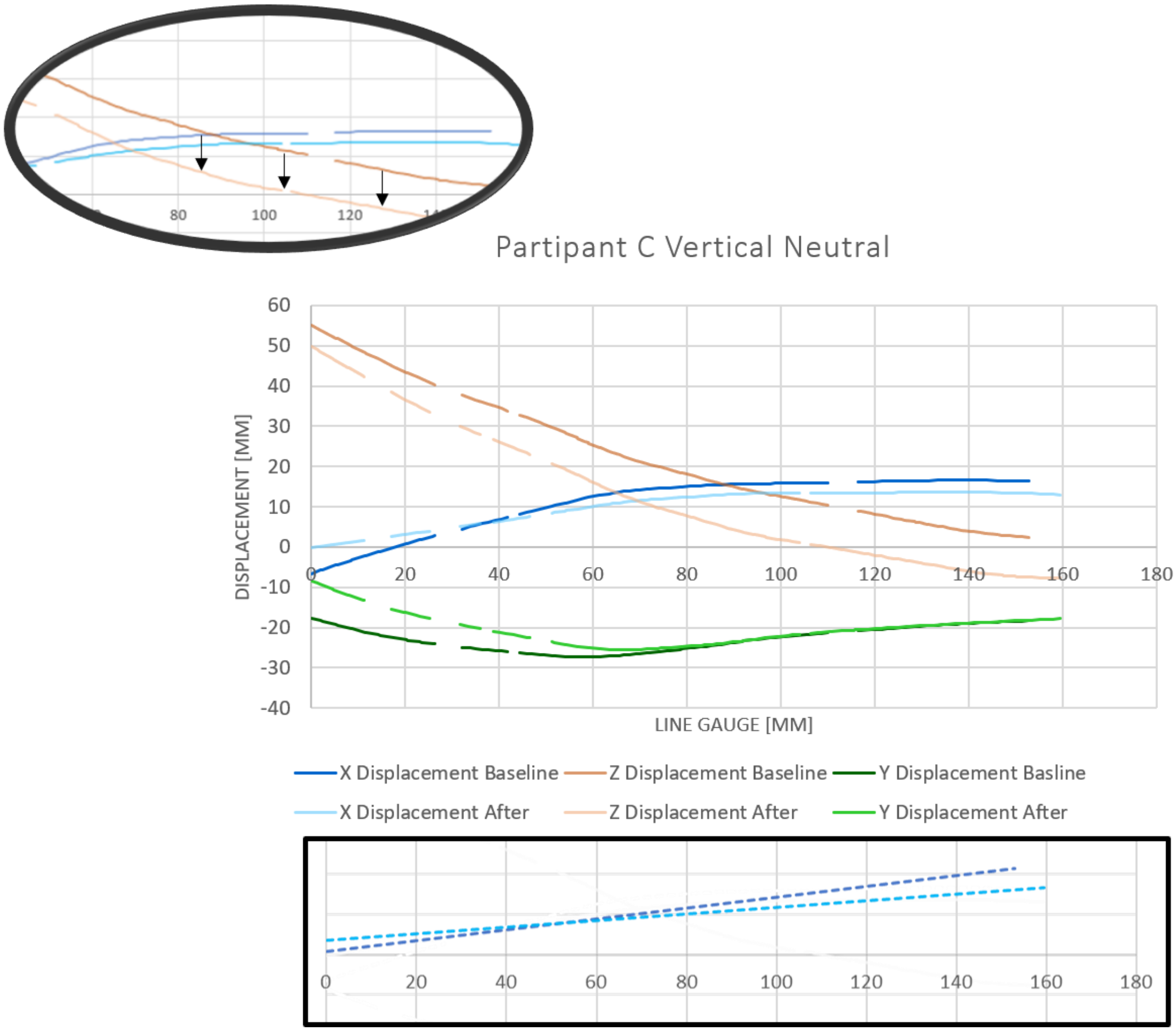

Figure 30. Vertical line gauge data for participant C for the displacement in the x, y and z direction.

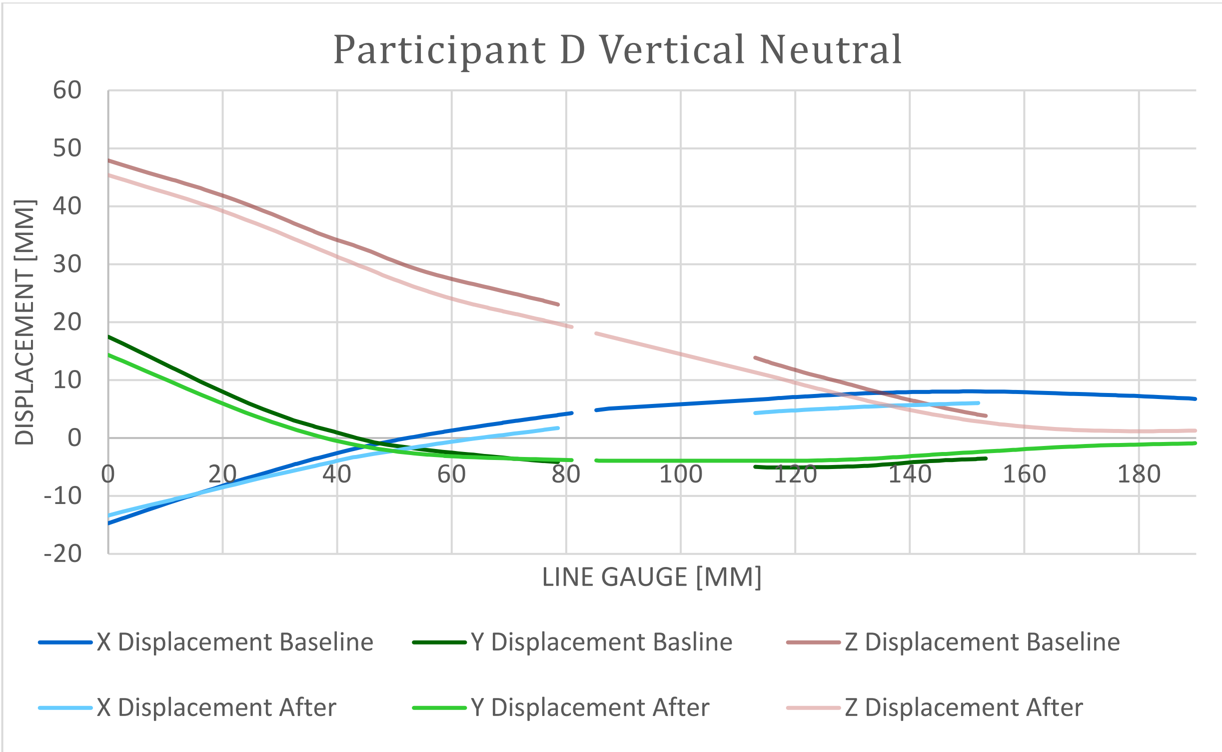

Figure 31. Vertical line gauge data for participant D for the displacement in the x, y and z direction.

Overall when assessing the hypothesis, it appears that banded squats did slightly alter the participant's motion. Specifically, in the x and z direction, as seen in the blowouts of Figure 30 do show that the after-displacement values are smaller in magnitude overall in comparison to the baseline data. The circle top blow out shows the decrease in z displacement and this can be applied to the data seen in Figure 31. The bottom blow out rectangle, shown in Figure 30 but can also be applied to Figure 31, shows the trend line in which the after x displacement slope is smaller as indicated by the flatter line. These trends, as shown by the blowouts, gives potential to future investigations that resistance training could indeed neuromuscular activate the proper muscles to keep unwanted movement out of the knee joint. In comparing data from a neutral stance and narrow stance, no difference was observed on the line gauge data and therefore not included in this section.

4.4 SUMMARY

Neuromuscular activation is used by athletes, physical therapists, and trainers to enact the proper muscles during specific movements. This training helps prevent injuries, redevelop muscle control, improve on technique and create correct muscle development. This study asked two participants to perform a banded squats routine to see the effects of resistance training on neuromuscular activation. The hypothesis that 3 sets of 20 banded squats would produce smaller displacement values in comparison to a baseline reverse squat measurement was tested. Proper muscle activation could help retrain women's' muscle control to prevent the valgus knee position. Valgus joint position, imbalance of muscles, and improper movement are a few factors that contribute to knee injuries in females.

Overall DIC was effective in identifying a valgus knee trend in participants. Reverse seated squats were performed and the system provided believable and correlated data for eight sets, proving the reliability of the values. A vertical line gauge was constructed down the center of the knee to test the hypothesis. The displacement data showed a consistently lowered absolute value for the x and z directions after banded squats were performed, thus a small change was seen after the resistance band routine. These results provide potential; however, the change is small and so further research with a more in depth kinesiology approach would need to be performed. For this study the thus the results are inconclusive, as changes were noted.

No data in either the line gauge analysis or the strain full field plots showed effects of participants' width stance. Strain data did provide useful information about muscle activation underneath the surface that could be used in the physical therapy fields as important notes, progress tracking values and overall a new tool for evaluating patients. Subject specific data produced from DIC would be useful for physical therapists as they evaluate one person at a time and observe all the tissues as one entity.

5. AGING SKIN STUDY

Section 5 is a comparative study between the knee of a 24 year-old female and 55 year old female. Many factors contribute to the deterioration of tissue as humans age. These effects become visually detectable by looking at the skin's surface. DIC however can produce data to show the effects of aging on the skin's behavior as well as the behavior of what is happening under the surface at the muscle and ligament tissue level. A mother daughter duo were compared to illustrate the versatility of DIC's analysis on skin in different stages of the aging process as well as provide the capabilities of what DIC can detect. Directional rigid body motion removal displacement data as well as strain data was compared.

5.1. EXPERIMENTAL DESIGN

As people grow older, their bodies experience compounding wear and tear. These factors cause signs of aging to be seen in the skin. The process is a combination of endogenous reasons like genetic, metabolic, and hormonal balances, as well as exogenous facts such as UV exposure, pollution, chemical, and toxins [53]. Consequently, skin will produce visible wrinkles, loss of mechanical strength and elasticity which can lead to sagging over time [25, 41]. Wrinkles occur from loss of muscle mass and skin thickness, loss of collagen, and dehydration in skin coupled with gradual wear over time. Facial tissue is a common example of skin that produces wrinkles [26, 53]. Blinking and mouth movements are performed numerous times daily. Skin in these areas experiences stretching and contracting repeatedly. As the aging process occurs, the elastic properties that once pulled the skin tightly back is no longer functioning as efficiently, leaving wrinkles commonly seen around the eyes, “crow’s feet” and mouth. Loose skin can be seen all over the body.

Figure 32. A) Bare knee of participant A as seen in the left image. B) Bare knee of participant B as seen in the right image.

This comparative study focuses on relating skin and knee movement of participants with a 30-year age gap. Figure 32 shows a side to side comparison of the participants’ knee. Just in visually analyzing, participant A’s skin shows signs of aging by the wrinkles in her skin around her knee. Much like the soft tissue around our eyes, the knee joint experiences daily movement and endless stretching and contracting of the skin. The application of the tattoo paper also highlights that participant A's skin is more advanced in the aging process. This is noted by the lined gaps in the pattern during a bent knee position as seen in Figure 33 below. Recall, the tattoo paper was applied when the joint is locked straight, and no gaps were visible. Figure 33 visually illustrates the lack of elasticity and looseness of skin when the knee is bent. The pattern is stretched further out and appearances of line gaps can be seen.

Figure 33. Participant A's bent knee and a blow out of the line gaps seen in the pattern due to aged skin. *Note the blow out image was taken from the side of the knee.

It is important to keep in mind not only the elasticity differences between younger and older individuals but also muscle deterioration known as sarcopenia that older adults experience from the natural aging process. Studies show that muscle mass decreases at an average rate of 1–2% per year after the age of 50 [31, 54, 55]. For reference, forty percent of the human body’s mass is comprised of the muscular system [56]. Voluntary muscles, such as skeletal muscles, are the tissues that control the mechanical systems required for body movements. Skeletal muscle tissue is responsible for posture and motion of the limbs and other body parts. It can self-repair and regenerate in response to damaged cells, but is not able to restore its properties in chronic degeneration such as sarcopenia[57]. Unfortunately, the aging process leads to a decrease in muscle mass, which in turns means a loss of strength [54, 58].

Participant	Age	Height	Weight	Q angle	Activities
A	55	5’8”	160 lbs	16.0°	Healthy HIIT work out 3x week Golf 3x week Walk 5x week
B	24	5’10”	150 lbs	16.0°	Healthy/Athletic Lift weights 4x week Cardio 4x week Sport 1x week

Table 5. Physical characteristics of the mother and daughter duo. Similar features and activities are observed.

5.2 PARTICIPANT PROCEDURE

Two participants were used for this study, one a 24 year old female and the other a 55 year old female who share endogenous traits as they are a mother and daughter duo. Their physical traits are listed in Table 5. Having related participants is beneficially as genetically the skin is very similar. Previously mention, skin’s behavior is dependent on age, genetic make-up and variety of exposures. By having a mother and daughter set, the genetic factor influencing skin type can be considered less influential as other traits such as the age and endogenous exposure. The genetically similar pair are both right leg dominant.

Both were asked to performed reverse block angle squats in which participants began the process in a seated position and lifted their body to predetermined angles. This was achieved by placing blocks underneath the squatters as needed. Note that a reverse block angle squat was chosen as it provided large stretching data of the skin and it was able to be performed by both participants. Balance and strength were both challenging when participant A attempted a reverse seated squat, which was the movement in the banded squat study. As a control variable, squat angles were defined and can be viewed in Figure 34 below and clearly outlined in Table 6.

Participants' movements were captured initially at step 0 with an 85° knee bend, followed by step 1 at a 100° knee bend, and finally at step 2 with a 110° knee bend. The skin around the knee deformed according to each angle and the data was compared between participants.

Step Number	**Angle of Flexion**
Step 0 (Reference Step)	85°
Step 1	100°
Step 2	110°

Table 6. Step number and bend angle of the knee for age study participants.

5.3 RESULTS AND DISCUSSION

5.3.1 RBMR DISPLACEMENT

When viewing the full field plots, the origin was redefined at the center of the knee. This was executed in a way that ensured consistency between participants and also allowed the joint to be broken into a quadrant system for discussion purposes as seen in Figure 35. Below is a series of plots that compare the rigid body motion removal (RBMR) in specific directions. The RBMR feature in DIC measures the stretching of skin instead of the entire movement of the knee. This benefit proves to be useful in measuring the motion of the human squats as it relates to the participants' skin movements, which are both translational and elongational. In the banded squat study, total directional displacements were analyzed, as the purpose was to understand the way women's knees moved. In this aging skin study, we want to exclusively look at only the manner in which the skin stretches and compresses. This is to analyze the characteristics of the skin and also to infer what muscle and ligament tissue is being used underneath the surface.

5.3.1.1 X RBMR DISPLACEMENT

To begin, Figure 36 shows the expansion of skin in the x direction for both participants. Step 1 and step 2 use step 0 as the reference. At step 0, the muscles around the knee are more relaxed as the participants were seated at a natural angle and the skin is expanded around the surface. Thus, the muscles are relaxed and contracted. Keeping this, the coordinate system, and the fact the right knee was observed in mind, negative values reflect the skin moving outward, or to the left. The purple negative values can be seen in Q1 and Q4 in participant A.

The higher positive red values seen on the outside of participant B's knee illustrate the curvature of the surface over the lateral collateral ligament (LCL) tissue. At step 0, the ligament is considered flexion such that the angle between the articulating bones of the knee joint is being decreased. Flexion motion causes the LCL to expand in size, similar to a muscle expanding. Thus at step 0 where the angle of the knee is at its smallest, the LCL swells pushing against the skin creating a smooth appearance from the outside surface. As participant B increases the angle of squat, the LCL relaxes and contracts inward. This is evident in the growing red region in Q3 of participant B. As the angle increases, the LCL shrinks and thus the skin moves inward which appears to as a positive movement in the x direction. Note that participant A does not show the LCL movement. This is due to the loose nature of the skin and the decreased modulus of the LCL. Like muscles, aging tends to change the mechanical properties of ligaments by physical shortening and loss of flexibility, a common precursor of OA or tight joints [59, 60].

5.3.1.3 Z RBMR DISPLACEMENT

Figure 38 shows the RBMR z direction full field plots. Note the range of values is the highest in comparison to the previous directions, x and y. This occurs due to the anatomical complex shape of the knee. The skin is experiencing maximum strain when stretching around the surface's curvature of knee. The negative values are indicative near the bottom of the knee where the joint moves backwards, away from the cameras. This backward movement is believable as the participants bodies are readjusting as their center of mass shifts during the series of flexion angles. If the upper body moves forward, then the lower must compensate and shift backward, hence the split between positive and negative values at the hinging knee. Note that the older participant has larger negative values, thus meaning she had to compensate for her imbalance that could be due to the lack of muscle strength that comes with age.   Once again, the data reflects a larger range of numbers for participant A, a common trend in this study.

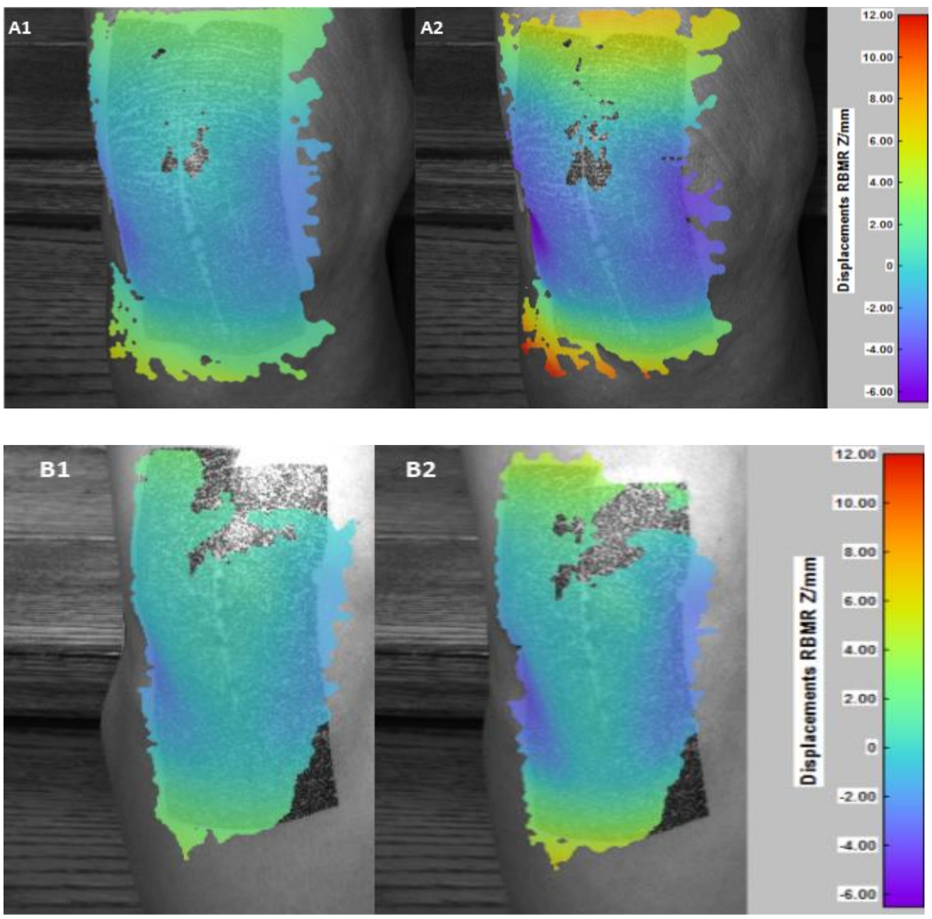

Figure 34. Rigid body motion removal z direction full field plot for participant A during block angle squats.

5.3.2 STRAIN DATA COMPARISON

Gauge features are offered in DIC software as a way to export data from a specific point or line. A vertical line gauge was carefully constructed using Instra 4D software for each participant for consistency during evaluation as seen in Figure 39. The following strain graphs show data for the line centered on the knee. Starting values of the line occur at the meeting of the patella and femur at the top of the knee. In the following sections, strain will be reflective of the skin stretching and compressing due to the angle of flexion, elastic properties of the skin as well as the behavior of biological tissue underneath the skin's surface. Tangential engineering strain or the Cauchy strain values were used and are calculated by considering both the deformation as well as the contour of the subject. Engineering strain, *e,* is expressed as a ratio. It is expressed as the change in length ΔL per unit of the original length L of the line element. Positive values indicate a stretching deformation and negative represents compression. Thus, the given equation is

$$e = \frac{\Delta L}{L} = \frac{\ell - L}{L}$$

Where e is the tangential engineering normal strain, L is the length of the evaluated area and l is the final length, after deformation.

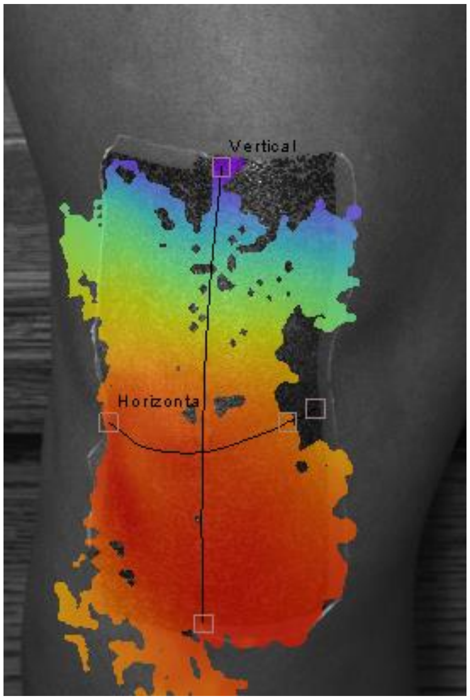

Figure 35. Example of line gauges that can be drawn in Instra 4D software. The vertical line gauge was used in evaluations.

5.3.2.1 ENGINEERING TANGENTIAL STRAIN X

The engineering tangential strain in the x direction, Figure 40, shows two distinct humps for both squatters, leading to the assumption that the skin behaves according to what is underneath the surface. In this case, the left peak is indicative of the patella, roughly line point 65 and shown on the top blow out, and the right reflects the top of the tibia bone, roughly line point 160 and shown on the bottom blow out. Skin covering a more rigid biomaterial like bone, will not experience as much motion as say skin positioned around muscular tissue.

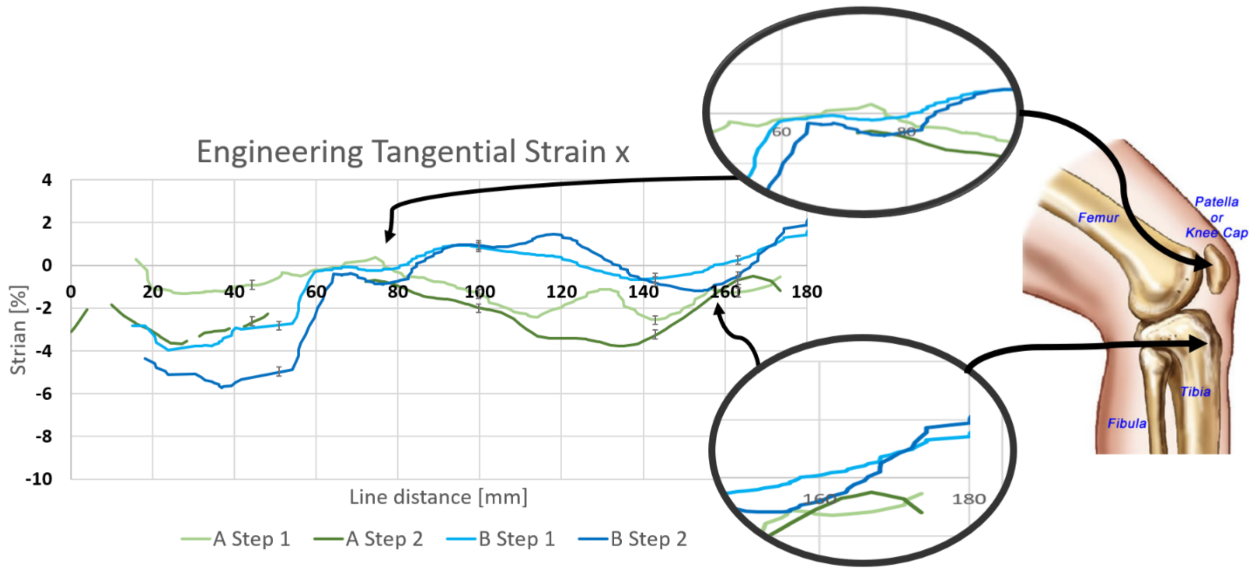

Figure 36. Vertical line gauge data for engineering tangential strain x. Blow outs show that skin has minimal movement over rigid bio tissue like bone [61].

Uncertainty for Engineering Tangential Strain x direction Error Bar Values							
A1		A2		B1		B2	
Distance [mm]	Error [mm]	Distance [mm]	Error [mm]	Distance [mm]	Error [mm]	Distance [mm]	Error [mm]
45	0.0648	45.6	0.052	45.6	0.009	45.6	0.023
100	0.062	99.5	0.297	99.5	0.028	99.5	0.045
145	0.322	145.5	0.022	145.5	0.006	145.5	0.020
165	0.005	164.9	0.092	164.9	0.003	164.9	0.028

Table 7. Error bar values for engineering tangential strain x direction. Distance refers to the line distance on the vertical line gauge and error is computed as standard error.

On either side of these distinct peaks, there is a larger variation between participants, which shows the dissimilar biological tissue behavior underneath the skin's surface. The opposite motion between roughly line points 80 and 100 reflects the comparison of ligament and muscle activity due to aging difference. In this region of local maxima for the younger participant, tissue activity is expanding the skin in the positive x direction. Muscles and ligaments that support and surround the knee expand and engage as the knee extends upward into step 1 and step 2. These ligaments and muscles are more active and the skin tighter around the younger person's tissue that the DIC captures this positive movement. Contrary, participant A's skin shows a negative movement in the x direction. This means the skin is contracting and pulling together, hence the negative values. As part of the aging process, participant A has experienced deterioration of muscles and also has lost elastic properties in her skin as proven in this data range.

In looking at the effect of angle extension on the engineering tangential strain in the x direction, both participants experience the same trend. As the knee moves out of flexion and into extension, we would expect larger values of tangential engineering strain values for higher angles.

Participants movements of the block angle squat was captured twice with the DIC system to ensure data was collected. A standard error calculation was used on four points of each data set to show the statistical accuracy of the results. Table 7 shows the values of the error bars seen in Figure 36. Uncertainty bars were calculated by first calculating the average of two participant trials for a specific point on the line gauge. The average was used to find the standard deviation and then this value was used to find the standard error.

5.3.2.2 ENGINEERING TANGENTIAL STRAIN Y

Engineering tangential strain in the y direction is shown in the graph below. Participant A shows more local minimas and maximas across the vertical line gauge as seen in the waviness of the green lines. This is reflective of the wrinkles within the skin. Over the years, gravity and additional wear has pulled on the skin causing sagging. The loose properties are reflected in the data of A as DIC captures the wrinkles compressing together. The top region of the knee, as seen in the top left blow out, for both participants show a large difference in strain values between step 1 and step 2. This occurs because of the motion that participants are performing as well as the behavior of tissue underneath the surface. At the top region of the knee, muscles are contracting and expanding during participants movements. Thus, a larger strain value is observed in the y direction. This softer tissue has more expandable movement compared to the rigid shin bone seen at the bottom of the line gauge. The blow out on the bottom right highlights that for all steps for each participant data lines are moving toward the zero-strain value.

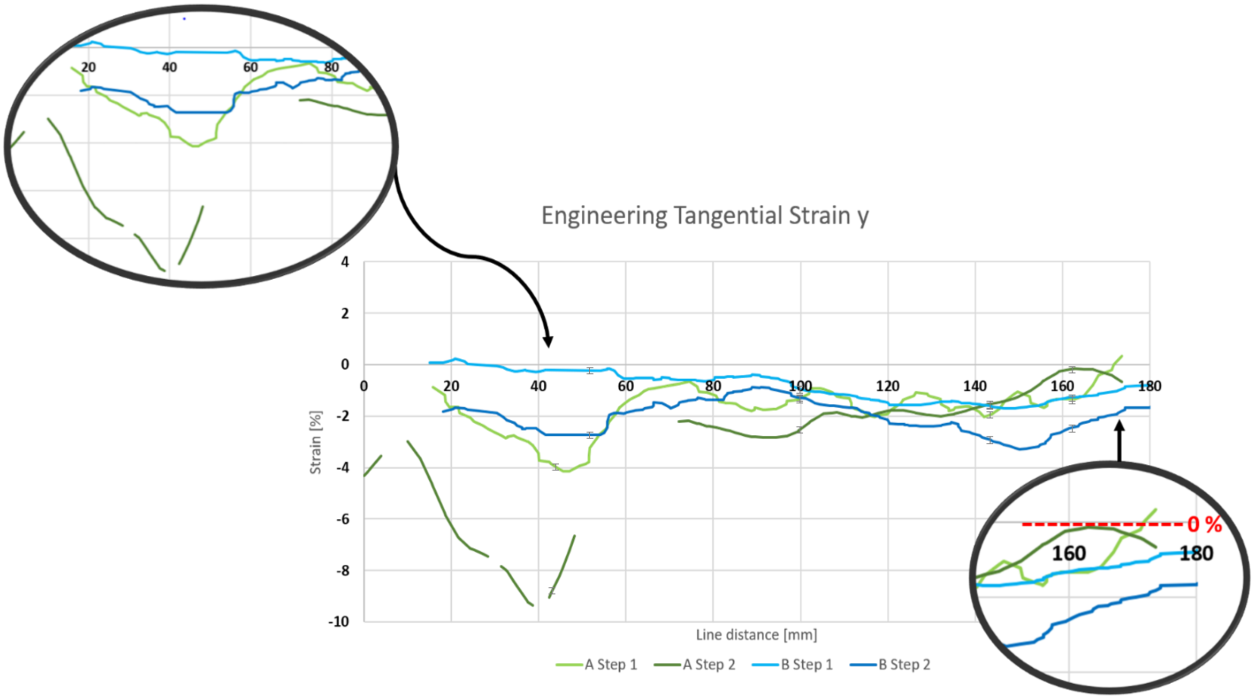

Figure 37. Engineering tangential strain y is shown for participants A and B. Blow outs are given to illustrate that the skin behaves according to what bio tissue is below its surface.

Uncertainty for Engineering Tangential Strain y direction Error Bar Values							
A1		**A2**		**B1**		**B2**	
Distance [mm]	Error [mm]	Distance [mm]	Error [mm]	Distance [mm]	Error [mm]	Distance [mm]	Error [mm]
45	0.496	45.6	0.147	45.6	0.010	45.6	0.012
100	0.115	99.5	0.082	99.5	0.006	99.5	0.048
145	0.306	145.5	0.044	145.5	0.004	145.5	0.007
165	0.098	164.9	0.007	164.9	0.022	164.9	0.004

Table 8. Error bar values for engineering tangential strain y direction. Distance refers to the line distance on the vertical line gauge and error is computed as standard error.

5.3.2.3 ENGINEERING TANGENTIAL STRAIN SHEAR

The below data is the engineering tangential shear strain for the participants. Shear strain values follow the same trend as seen in the x and y directions: there is an increase absolute strain value with an increase of angle extension. Overall, participant B experiences less twisting of the knee as the shear strain remains positive. This can be related to the younger participants muscle strength maintaining a more rigid knee position. A trend line interpretation of the data clearly displays that participant A experiences more movement in her skin. Again, this is a result of the aging process. A worn rubber band allows more movement to occur because of the lack of elastic properties.

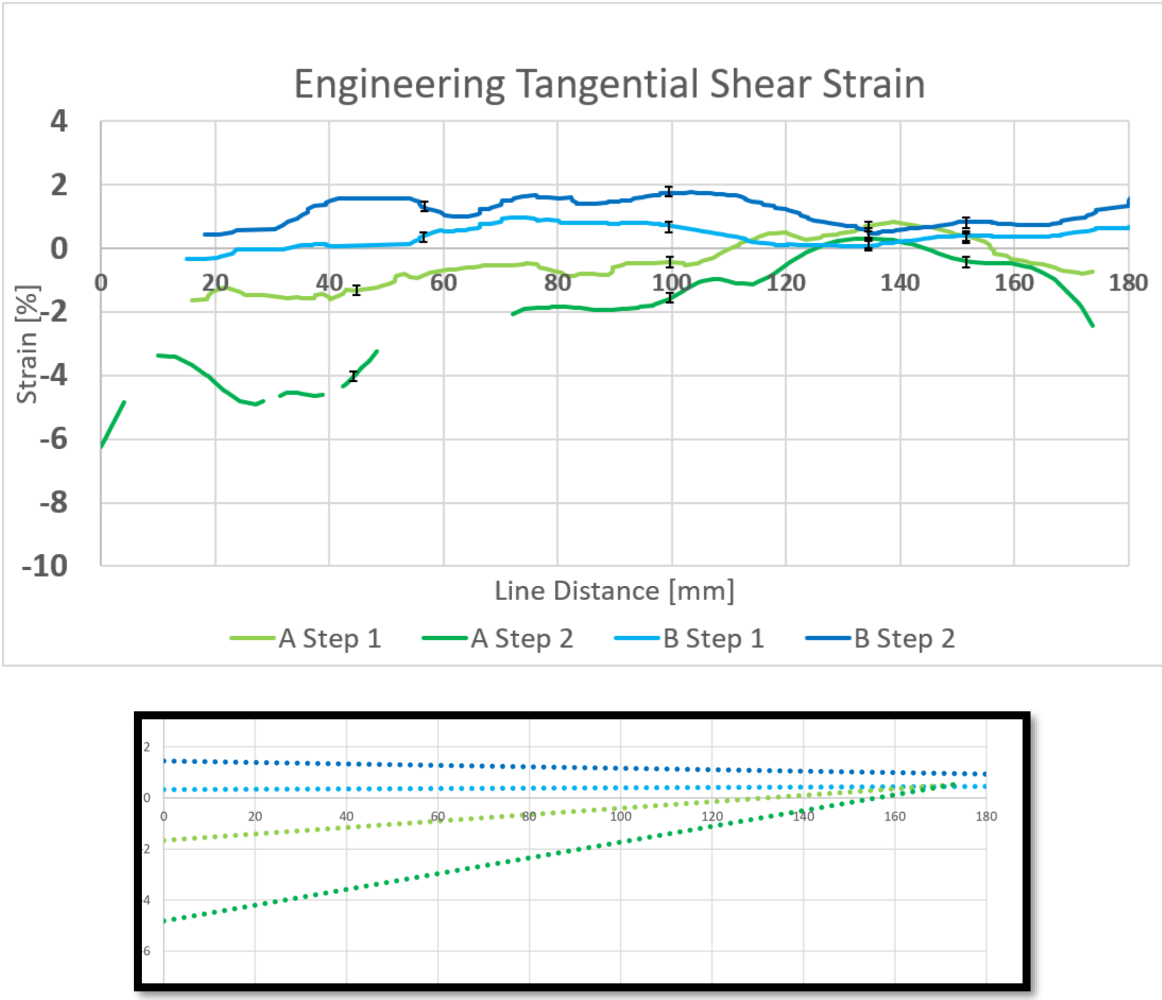

Figure 38. Engineering tangential shear strain for participants A and B. A trendline showcases that the older participant has larger variation in strain values.

Uncertainty for Engineering Tangential Strain shear direction Error Bar Values							
A1		**A2**		**B1**		**B2**	
Distance [mm]	Error [mm]	Distance [mm]	Error [mm]	Distance [mm]	Error [mm]	Distance [mm]	Error [mm]
45	0.301	45.6	0.019	45.6	0.005	45.6	0.016
100	0.077	99.5	0.128	99.5	0.006	99.5	0.029
145	0.040	145.5	0.037	145.5	0.003	145.5	0.028
165	0.037	164.9	0.022	164.9	0.004	164.9	0.003

Table 9. Error bar values for engineering tangential strain shear direction. Distance refers to the line distance on the vertical line gauge and error is computed as standard error.

As on overview, the average of strain of the vertical line gauge was calculated. In Figure 43, the absolute values of these averages are seen to compare the overall magnitude of strain. It is clear the older participant, A, has larger strain values for each direction. This is due to the overall lack of elasticity of the skin. By comparing the average on the line gauge, it can be seen that overall the skin for the older participant allows more movement due to its lack of elasticity.

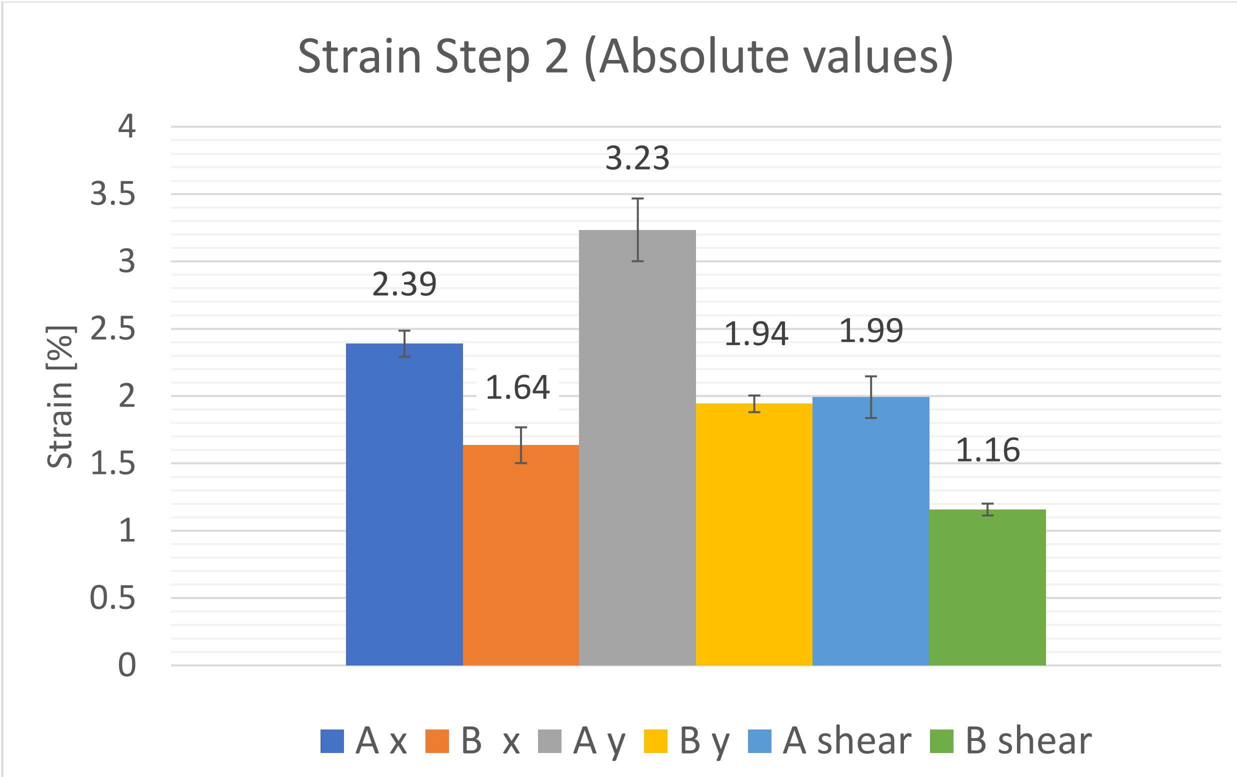

Figure 39. Absolute values of the average strain for step 2 for participants A and B.

5.4 SUMMARY

Section 5 investigates the effects of aging on skin around the knee joint. A mother and daughter duo were compared during a block seated angle squat in which the knee was in different stages of flexion and extension. Overall, the loss of ligament and muscle activation as a consequence of aging was seen in the full field plot analysis in all RBMR directions. Loss of elastic properties in the layers of skin were also evident in participant A. Absolute values for strain were higher for step 2 compared to step 1 which reinforces expectations; the skin experiences more movement with a larger extension. DIC proved to be an effective tool in examining properties of aging skin that will be useful in the cosmetology and beauty field. This data will further supply information on elastic properties to rejuvenate and revitalize skin as well as provide tools to supplement the ongoing investigations of OA. As seen in the full field plots, ligaments and muscle mechanics are evident from the skin surface and therefore could help link OA to joint deterioration.

6. CONCLUSIONS AND OUTLOOOK

6.1 CONCLUSIONS

This thesis explored the feasibility of digital imaging correlation (DIC) as innovative approach to providing data on active living humans. Knees were studied due to their high rates of injury and disease, as well as their complex geometry and variety of synchronized biological tissues. Specifically, female joints were observed, as women are more susceptible to ligament tears and osteoarthritis. Furthermore, an novel method to pattern application was created which potentially could advance DIC systems into a professional capacity.

The following points are highlights of the major accomplishments and conclusions of this work that were detailed in the previous sections:

1. **Temporary tattoo paper**, also known as wet transfer paper, was used as an alternative to painting methods that were popularly applied in past research methods. Benefits of temporary tattoo paper include…
   a. Non-toxic properties
   b. Printable → easily scalable for a variety of FOV's
   c. Uncertainty is minimal and known
   d. Easy to apply
   e. Comfortable application process for participants

A test comparing the bare skin and tattoo paper produced results that concluded the tattoo paper did not hinder the skin's behavior.

2. **Pattern development** was fabricated through photo editing software and a specific pattern was developed to fit around the knee at a FOV that could capture the motion of a squat performed by participants. The pattern was a combination of 175 DPI and 150 DPI scale that was fabricated to account for the camera angle downward as well as the curvature of the knee.

3. **Successful data collection** was obtained for eight different trials as similar trends were captured by DIC in the banded squat study. Participants had very similar physical characteristics as well as physical habits. Thus, similar data output from the DIC system would be expected and proved the reliability of the technology.

4. **Valgus knee trend** was effectively captured by the DIC system. The inward motion of the knees during flexion is a large contributor to injuries. This is a key finding because now that it has been proven that DIC can identify the problematic trend, its technology can be used to track performance and evaluate techniques in correcting the valgus knee position.

5. **Aged skin** was evaluated by the DIC system, which proves the feasibility of DIC on a variety of skin types, thus creating opportunities to explore research concerned with osteoarthritis, wrinkled skin and sarcopenia.
    a. Full field plot figures captured the aging effects of less elastic skin, as the older participant shows plots with higher variations for rigid body removal displacements. This larger range of values indicates that the older skin has

more movement. Also, a vertical line gauge centered down the middle of the knee captured larger strain values for the aged skin in x, y and shear tangential engineering directions. This concurs with the aging process, as the skin is less elastic and allows larger movement in comparison to a younger participant.

   b. The effect of sarcopenia can be seen when contrasting the region of the lateral collateral ligament, LCL, of the older participant with the younger. The younger participant's LCL is seen being active through the vivid and distinct color variation in the full field plots. In comparison, the older participant's LCL was not visually apparent in the full field plots.

6. **DIC captures the systematic unit** of the joint, in which the skin deformation cannot be accounted for with-out the ligaments and muscles behavior. The driving force of the skin straining is the movement of biological tissue underneath its surface.
   a. The age study shows the sarcopenia aging effects, as the DIC captured a negative strain value over the patellar ligament for the older participant. The negative value suggests the ligament has less elasticity and lost flexibility over time. The younger participants showed a positive value for the region where the patellar ligament moves. This indicates that the younger participant's ligaments are still active and have not endured deterioration due to the aging process.

6.2 OUTLOOKS FOR FUTURE APPLICAITONS

In proving DIC is applicable to living humans many benefits can be achieve.

- Overall DIC will be a new technique to analyze human skin and other biological tissue. The method provided by this study is non-invasive, non-harmful, cost effective, quick to apply and reliable.
- Understanding skin movements can provide information into what is happening under the surface, which can be applied to a variety of fields of study.
- DIC systems can provide useful data to understand aging skin and can be supplementary to ongoing research projects that analyze diseases and prevention of osteoarthritis and sarcopenia.
- DIC can be implemented into a variety of biological fields below are just breaking the surface:
    - Bio-engineering and orthopedic surgeons can use DIC data in creating prosthetics or bio-materials
    - Physical therapy can utilize this equipment to look at muscle activation and track progress
    - Plastic surgeons can have a patient specific data to reduce surgery mistakes, like botched facelifts
    - Cosmetology fields can use DIC technology to better understand the effects of products, like Botox

- Physicians can utilize the 3-D data to have patient specific models that can be used in computer aided surgery

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