Exploring the Utility of Motion Capture to Provide Feedback to Nursing Students During Injection Training

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Abstract

Intramuscular injections are a standard procedure performed by nurses. The literature analyzing the injection procedure and the effectiveness at which nurses execute it has reported errors due to technique and even conflicting guidelines on injection technique. Insufficient data is available regarding the kinematics of intramuscular injections, underscoring the necessity for further investigation to gather knowledge on the critical aspects of proper injection technique. These include injection angle, velocity, and rate. This research aims to develop a practical, easy-to-use, and accurate motion capture system to collect data on the kinematic attributes of an injection. The end goal for the system is to be used in a study to collect data on the injection kinematics of multiple nursing students to assess the system's effectiveness in training applications. Different computer vision motion capture systems were explored and compared to determine the most appropriate for the application. A system was developed using an Intel Realsense D455 depth and computer vision techniques to identify injection velocity, rate, and angle. The camera identifies color markers placed on the syringe to detect its position and motion. This has been able to produce tracking with consistency upwards of 98% and quantifiable measurements of the injection kinematic

Introduction

The healthcare industry is consistently improving the quality of care it can deliver to patients. Advances in medication and technologies are the main drivers of constant progress in the efficiency and effectiveness of treatments. Technological advances usually come in the form of new tools that can be used in a hospital setting, such as ultrasound transducers and other imaging devices, electronic health records (EHRs), surgical devices, and more. As great as these advancements are, they are useless without nurses and doctors with the knowledge and skills to use them. Improvements in nursing are made through education by maintaining core values such as critical thinking, but also by adopting new tools to improve the quality of education. Most notable technological advances are in high fidelity simulation labs, but there are always limits to simulating the experience of caring for a real patient. Nevertheless, there seems to be an opportunity to leverage more modern technological capabilities to improve the quality of education. One form of technology that is now fairly accessible to the general public is motion capture systems. This enables individuals to record, measure, and visualize in real time the exact kinematics of a desired subject, in most cases the human body. There are a plethora of procedures, which are subject to change, that a nurse must be able to carry out with the proper steps and techniques. This paper proposes a proof of concept motion capture system that can be used to collect kinematic data of a procedure and provide feedback to nursing students. The system will be focused on injection procedures.

In reviewing the errors made by novice nurses, Ebright et al. found "a significant portion of the reported errors occurred when the novice nurse was doing a procedure with which they had little or no experience" [21]. Novice nurses are not expected to be familiar with every procedure in health care, but it would be desirable to increase the amount of procedures nurses coming out of school are familiar with. Ebright et al. also notes “It is estimated that 75% of novice nurses commit medication errors (which includes errors in the administration of intravenous infusions, … Another study that tracked types of errors in novice nurses showed that as many as 88% of the errors involve medication and intravenous infusions,” [21]. If errors in administering medication are the most common, it would be logical to elevate the teaching of those procedures. Injections and infusions are procedures which require precise and unique technique dependent from case to case. Motion capture is a tool that can record precise information about the position and movement of the people and tools involved in these procedures. This data could prove to be extremely helpful in giving a nurse feedback on their performance, data analysis of technique parameters, and setting guidelines for procedures.

Background: Injection Types

There are a wide variety of injection types which deliver specific medications to different locations in the tissue. Of these various injection types, one of the most common, especially due the prevalence of the COVID-19 virus, is the intramuscular injection (IMI). While studying a nursing staff, Fekonja et al. state, “99.5% of participants reported they administer up to nine IMI per day” [2]. As the name may imply, an intramuscular injection is any medication that is injected into the muscle. This allows “larger volumes of drug [to] be injected due to the rapid uptake into the bloodstream through muscle fibres” [1]. Antibiotics, biologicals such as immunizations and vaccines, and hormonal agents are some of the most common medications that are delivered intramuscularly [24]. Due to the large demand for vaccines in recent years, injection education in nursing schools has been primarily focused around IMI. Anecdotal reports from clinical instructors at the University of Massachusetts Amherst highlight this focus and express the nursing students’ unfamiliarity with other injection types such as subcutaneous.

Medications for subcutaneous injections are delivered into the fatty (subcutaneous) layer of tissue sitting just below the skin. It is “chosen when slow, continuous absorption of the drug is required, for example insulin and low molecular weight heparin” [11]. This is a shallower injection which requires a different technique from IMI, but intradermal injections go even shallower into the human flesh and require even more precision. Intradermal injections are less common and usually used for tuberculin and allergy testing where low volumes are deposited just below the epidermis [25]. Arguably the injection which requires the most precision is the intravenous (IV) injection, or injections into the vein. This procedure requires multiple steps if a catheter needs to be inserted into a vein. A catheter surrounds the needle which enters the vein first, then the catheter is pushed down the shaft of the needle and fed into the vein, after which the needle is removed. This requires precision, steady hands, and specific handling of the injection tools and patient. Jacobson et al. claim that IVs are the most common invasive procedures performed by nurses, yet in their study, a fourth of 339 observed IV insertions were unsuccessful [26]. This is a high rate of failure for such a common procedure which can cause “vein and nerve damage, hematoma, and neuropathic pain” according to Fujii [18]. Both Fujii and Jacobson et al. highlight the lack of research and data analysis of failure in this procedure, providing motivation for capturing motion data of this practice.

Nurse Training / Education

As stated before, the Elaine Marieb College of Nursing at UMass Amherst has reported that the vast majority of injection training pertains to IMI due to the high demand for vaccines in recent years. This is subject to change and Clinical Instructor, Tracey Cobb, expects subcutaneous injections to become a higher priority in coming years. This requires a different technique and a more delicate touch according to Rodger and King since “under the muscle fascia has fewer pain sensitive nerves than subcutaneous tissue" [1]. The emphasis on proper technique is expected to elevate, thus a tool to improve the performance of nurses in training could prove to be very useful.

Currently, nurses learn how to administer certain injections based on the literature recommended by their curriculum and professor instructions. It has been found that the literature describing the parameters of injection techniques are not always consistent, resulting in variation throughout the practice. Petousis-Harris states:

> Prior to 2002 there were almost no published studies investigating the optimal technique for delivering intramuscular injections. This has led to inconsistencies in recommendations and practice as well as disagreements as to how vaccines should best be administered [15].

This sheds light on the need for data collection of injections. Additionally, anecdotal reports claim little time is spent in the nursing curriculum on the practice of administering injections, while students show a lack of dexterity and confidence in performing the procedure. A system which provides nurses in training with feedback could be conducive to accelerating their learning curve.

Kinematic Parameters: Injection Angle

One injection parameter that greatly influences the success of the injection is the angle at which the needle is inserted into the tissue. This is specified to ensure the needle reaches a certain depth depending on the type of injection. For intramuscular injections "Authors such as Craven & Hirnle (1996), Berger & Williams (1992) and others advocate introducing the needle into the site at 90 degrees" [1] while Pope suggests a 80-90 degree angle of insertion [13]. Petousis-Harris recognizes 90 degrees as the most popular specification for IMI angle and presented the following guidelines recommended by various sources [15]:

Source	Angle (°)	Site	Aspiration/speed	Length	Gauge
CDC	90°	Deltoid >12 months	No/NS	1 in.	20–25
WHO	90°	Thigh, deltoid for older infants	No/withdraw needle quickly	25 mm	23
IAC	90°	Deltoid >12 months	No/rapid	1 in.	22–25
AAP	90°	Deltoid >12 months	No/rapid	16 mm <12 months then 25 mm	NS
Canada	90°	Deltoid >12 months	No/NS	1 in.	22–25
UK	90°	Deltoid >12 months	Yes	25 mm	NS
Australia	60°	Deltoid >12 months	Yes/slow	25 mm	23
New Zealand	60–70°	Thigh <15 months	NA/controlled	16–25 mm	NS

	Or 90°	Deltoid >3 years	Not addressed		
New Zealand (MeNZB)	60–70°	Deltoid (8–12 years)	Yes/slow	25 mm	20

NS: not specified; CDC: Centres for Disease Control (American); AAP: American Academy of Paediatrics; WHO: World Health Organization; IAC: Immunization Action Coalition.

Figure 1: Intramuscular Injection Angle Guidelines [15]

The table shows there is not a unanimous consensus on the angle parameter. Marshall et al. performed a study comparing 60 to 90 degree intramuscular injections, to evaluate for their success in injecting the medication into the muscle. This was confirmed or refuted using an ultrasound machine which found that 13/15 or 87% of administrations at 60 degrees were successful while 16/17 or 94.1% of administrations at 90 degrees were successful [19]. Although there is a slight difference in success rate, the sample size is small. More data would be useful in confirming the discrepancy, but this confirms the ambiguity behind injection angle. Katsma explains, “the rationale for the 90°-angle intramuscular injection is that as the angle of the injection deviates from 90°, the depth of the injection decreases” [16]. But simple trigonometry shows that small deviations from 90 degrees will have a very small impact in the actual depth. Figure 2 demonstrates this.

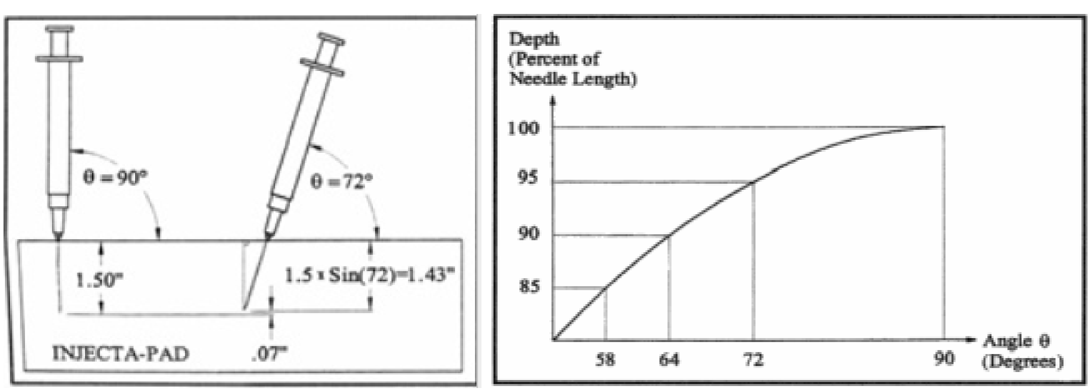

Figure 2: Needle Depth vs Angle [16]

Even at a 72 degree angle the depth only decreases by 5% from the maximum. Katsuma concludes that the angle for IMI does not have to be precise but the nurse should rather focus on using a comfortable hand position that will allow them to smoothly insert and remove the needle.

The angle of the needle and the actual length of the needle go hand and hand. For IMI, Beyea and Nicoll recommend “for adults, select a 1.5-in needle. For children, select a 1-in needle. Use a needle of 21-23 gauge” [9]. Marshall concurs with Beyea and Nicole, recognizing a 1.5 inch needle as the standard for adult IMI. Contrarily, Pope recommends a needle length of 0.5-1 inch for deltoid IMI and 0.5 for other locations (glute) in adults [13]. Rodger and King do not sit on either side of this disagreement of guidelines, they remark, “Needle size and dose is determined by palpating/pinching the fat and adding on a set length depending on area” [1]. They recommend this method since needle size guidelines are hard to establish while accommodating for different thicknesses of the subcutaneous layer of fat. Miscalculating the depth needed to reach muscle tissue for an IMI proved to be a problem in a study conducted by Cockshott et al. They utilized computer axial tomography (CAT) scans to determine where the medication injected into the dorsogluteal region by nurses was actually deposited. Results showed that “under 5% of the women and under 15% of the men would have actually received an intramuscular injection into the glutei” [4].

There are also inconsistencies in the guidelines for subcutaneous injection angles. Some sources set a loose range between 45 and 90 degrees depending on the length of the needle, with the 45 degree angle being recommended for needles longer than 8 mm (0.31 in) [10] [13]. Hunter sets the standard at 90 degrees which adjusts to that angle depending on the available subcutaneous tissue. She claims that accidental insertion into the muscle rather than the subcutaneous tissue will affect the rate of absorption and can cause the patient harm. She goes on to say this error is due to “a poor understanding of the technique” [11]. This alludes to the intuition and subjective judgment of the nurse which is required, to an extent, in most medical procedures. Although, that is not to say that feedback and more detailed guidelines on injection administration could improve a nurse's execution of the procedure.

The inconsistencies in angle specification could also be attributed to developments advocating for one technique over another. Martires et al. conducted a study, collecting patient feedback on how painful an injection of Lidocaine was at 45 degrees compared to 90. They reported the average and median pain experienced by 90 degree injections was lower than the 45 degree injection [17]. They hypothesized that the 90 degree injection was less painful because it was found to require less energy (in turn less force) than a 45 degree injection in a study conducted by Egekvist et al. [3]. Cocoman and Barron also acknowledged that with the introduction of shorter needles, “practice has changed from administration at a 45-degree angle to a 90-degree angle” [20]. With medical procedures constantly changing, a tool to enhance the learning of new techniques could expedite the education process and produce nurses with more uniform skills.

Intradermal and Intravenous (IV) injections require the shallowest angle of administration. Intradermal injections are shallower than the average IV with a recommended 10 degree angle between the skin and needle [25]. As one could imagine, this also affects how the nurse would hold the needle with their hand compared to a 90 degree injection since there is less of a concern of the patient's body obstructing the nurse’s hand. Different hand placement is also used for IVs, since two hands are needed to manipulate the needle and catheter. The angle of IV injections vary depending on the patient, but there is a severe lack of data on the average angle in which IVs are administered. In one study, Fuji reported angles of IV administration on 64 subjects ranging from 10.7 to 21.8 degrees with a mean of 15.2 degrees [18]. Fuji remarks that there are no other experimental studies, to their knowledge, to compare these results to. For such a common practice in nursing with such a high rate of failure, ~25% [26], there is a need for data collection of the kinematics involved in this procedure.

Kinematic Parameters: Velocity

The velocity of needle insertion is a kinematic parameter which has not been outlined and studied thoroughly. Most sources describe this parameter by stating, "insert the needle smoothly" [11], "quick dart-like motion" [1] or "insert the needle with a steady pressure." [16]. A study conducted in 1997 is one of the few to record kinematic parameters of IMI. They compared novice nurses to experienced nurses and found their average peak velocities (+/- SD) to be 817.1 (+/- 250.7) mm/s and 606.9 (+/-) 285.6 mm/s [5] . Novices showed to have quicker injection velocities which somewhat disagrees with Egekvist et al. 's findings, assuming more experienced nurses deliver less painful injections. Egekvist et al. reported greater pain qualities to be correlated with slower injection speeds when comparing 2 mm/s and 19 mm/s injection velocities [3]. Another explanation is that nurses' attention to detail in their technique wanes in time. The 1997 study reported the average angle of IMI for novices was 82.5 degrees whereas experienced nurses averaged 75.6 degrees [5], further off from the common 90 degree recommendation. Although this difference in angle should not be significant for reasons stated previously. Jacobson et al. analyzed the success of IV administrations executed by nurses ranging in experience. They concluded that successful insertions were generally executed by more experienced nurses who completed them more quickly.

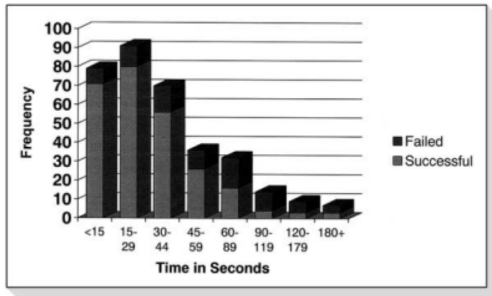

Figure 3: Frequency of Success and Failure of IV administrations vs Time to Complete [26]

Granted, this does not necessarily mean higher injection velocity because only the time to complete the entire procedure was measured. This information would be very useful to establish guidelines for instructing IV administration. Velocity is a useful parameter for nurses to know since it influences depth of injection and pain experienced. Kinematic data can also help identify poor technique not only in novice nurses, but experienced nurses as well.

Injection Rate/Volume

The rate and volume of a given injection can and does often result in various intravenous-related errors. A study in 1996 outlines a " high incidence (up to 90%) of bruising from any subcutaneous heparin injection techniques" [12]. This clearly demonstrates an area of training that could benefit from a revised education or training program. In literature concerning the current precedent for injection rate and volume, consistent evidence was shown for 1 mL every 10 seconds being an effective rate [1] & [9]. These studies also suggest a 10 second waiting period after injection before withdrawing the needle. However, another study reveals decreased site-pain intensity when injecting over a 30 second period [12]. Inconsistent and ambiguous statements in injection rate guidelines call for further data collection. Motion capture would be able to measure the velocity of the syringe's plunger, thus the injection rate, providing a means of data acquisition. As seen in the table below, 73.3% of intravenous-related errors are at least partially due to an incorrect rate and 33.3% due to wrong volume [23].

Table 3 Type and severity of intravenous administration errors

Type of intravenous-related error	Number of errors (%)	Number of errors rated as serious (% of intravenous error type)
Wrong rate	266 (73.3)	95 (35.7)
Wrong volume	121 (33.3)	21 (17.4)
Wrong mix	21 (5.8)	5 (23.8)
Drug incompatibility	3 (0.8)	1 (33.3)
Total intravenous administrations with at least one clinical error	363*	99* (27.3)

*Sums exceed totals because of multiple errors within the same intravenous administration.

Figure 4: Type and Severity of Intravenous Administration Errors [23]

Fixes in training regarding these two areas would result in significant decreases in intravenous administration errors.

Hand and/or Body Position/Form

Another influential factor of administering injections, which is often overlooked, is how the non-dominant hand and rest of the body is positioned relative to the patient. Injections, for the most part, are two handed procedures. One hand holds/manipulates the syringe while the over holds and manipulates the patient's body around the injection site. Some literature in IMIs guides nurses to stretch the skin at the injection site with the thumb and forefinger of their free hand [6]. Other literature outlines a “Z-track technique” which involves pulling the fatty tissue “1+/-1.5 inches” to the side of the injection location [1]. This is meant to better seal the medication in one location and prevent it from leaking to unwanted parts of the tissue. Another technique of pinching the skin to “lift the adipose tissue from the underlying muscle” is suggested for subcutaneous injections, in order to prevent IMI [11]. Other sources lay out detailed guidelines on how to position the patient’s entire body, for example, “In a prone position, the patient can be instructed to "toe in," which internally rotates the femur. In a side-lying position, the upper leg can be flexed 20° to ensure internal rotation” [9]. This technique can help relax the muscle and allow the nurse proper access to the injection region. This also extends to how the nurse positions theirself, for certain procedures. Figure 5 outlines various responses from nurses on technique tips for administering IVs:

Table VII
Techniques or "tricks" used by nurses to facilitate IV insertion

Category	Actual nurse responses	Frequency
Position self	Stand, usually stand, always stand, sit down, sit down at bedside on chair or window sill, always sit down, get self in position so don't have to bend over (sometimes stand, sit, or kneel), squat or sit if need to use hand, kneel	18
Use mechanical stimulation	Flicked vein, tapped vein, rubbed vein, slapped site, rubbed with ETOH, rubbed vein, massaged vein, mashed vein to make it stand out, used increased friction/duration while cleaning site, rubbed arm downward	16
Stabilize vein	Stabilized vein, anchored vein, positioned to hold vein in place, pulled skin taut	15
Individualize tourniquet use	Did not use tourniquet, no BP cuff, released/reapplied tourniquet to bring up vein, had tourniquet on and off several times, used BP cuff instead of tourniquet, lowered arm and then placed tourniquet	9
Individualize threading technique	Threaded slowly, threaded gently, floated with IV going, threaded with fluid going, kept stylet in until completely threaded because of tough skin, when initial flashback stopped pushed needle above initial insertion site and threaded with difficulty, played with JELCO (advanced and pulled back)	9
Position arm dependent	Put arm off side of bed in dependent position, had patient let arm hang straight down, lowered limb	8
Position bed	Raise bed, bed elevated, bed in air, keep bed low, raise head of bed	7
Enhance vein visibility	Left skin wet with ETOH so could see vein better, vein only partially visible so palpated entire vein, shaved hair on arm, used exam light, closed eyes to feel for vein, did not use Betadine because obscures vein	7
Use lidocaine	Used lidocaine before insertion, 0.1 mL intradermal lidocaine, local anesthetic to decrease anxiety	6
Use heat	Applied moist heat, used warm towel	6

Figure 5: Techniques used by Nurses to Facilitate IV Insertion [26]

Many of these use relative positioning to improve the success of the procedure, motivating the new technical usefulness of collecting kinematic data to support certain techniques or improve upon them.

Injection Kinematics and Forces Current Research

There has only been one published study on the kinematics of a needle during injections to the author's knowledge. Katsma et al. compared the needle motion between novice and experienced nurses for IMI. They used "video motion analysis techniques" with a VHS camera to record subjects administering 5 IMIs into InjectaPads [5]. They were able to produce the data featured below.

Variable	Novice	Nurse	Probability
Vertical displacement	129.6 ± 31.4 mm	92.6 ± 32.8 mm	$p < .0001$
Horizontal displacement	23.4 ± 13.3 mm	23.3 ± 14.1 mm	$p = .983$
Depth	33.4 ± 4.1 mm	33.7 ± 4.1 mm	$p = .884$
Peak velocity	817.1 ± 250.7 mm/s	606.9 ± 285.6 mm/s	$p = .003$
Contact velocity	743.1 ± 240.7 mm/s	544.0 ± 296.3 mm/s	$p = .005$
Horizontal component of contact velocity	55.4 ± 35.2 mm/s	−34.8 ± 148.4 mm/s	$p = .835$
Path width	2.29 ± .9 mm	2.9 ± 0.1 mm	$p = .023$
Angle at contact	82.1 ± 7.1°	75.6 ± 9.7°	$p = .005$
Angle at completion	85.5 ± 5.3°	78.2 ± 9.5°	$p = .0005$
Delta angle	4.5 ± 4.5°	2.3 ± 4.2°	$p = .433$

Figure 6: Kinematic Parameters of IMIs [5]

Peak velocity, angle at contact, and vertical displacement show the highest discrepancies and are parameters of interest. This study was conducted 25 years ago, an updated study using more advanced motion capture equipment could shed new light on injection technique and provide a cross examination of data. An automated motion capture system could even be created to give a nurse feedback on their kinematic performance.

Other research has been conducted to attempt to aid in the administration of injections. One paper by Lorenzo et al. reported on their development of a "novel robotic coaxial needle insertion assistant" [14] which amplifies force experienced on the needle tip during an injection so the operator can feel when the needle enters a different type of tissue. They reported that this has increased the frequency of tissue change detection by "up to 50%", presumably giving the operator a better “feel” for where the needle is located in the tissue. The success of haptic feedback to increase a nurse's knowledge and/or confidence motivates exploration into other modes of feedback such as visual or audio. The evaluation of this insertion assistant also yielded useful force data.

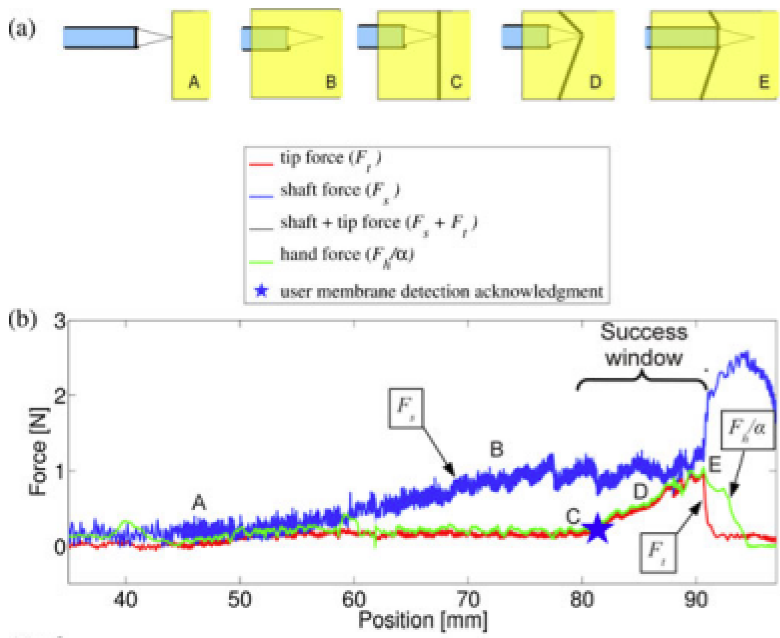

Figure 7: Force Experienced by Needle Tip Data [5]

Force data can be related to parameters discussed throughout this review including needle size, insertion technique, and tissue properties. The downside of this tool is that it is large and not realistic for use in actual practice. For this reason, motion capture tools that do not obstruct the procedure at all are being explored to validate if they can deliver accurate information about position, angle, velocity, and possibly even force.

Jiang et al. studied the forces a needle experiences during injections as well, some of their results are shown below [22].

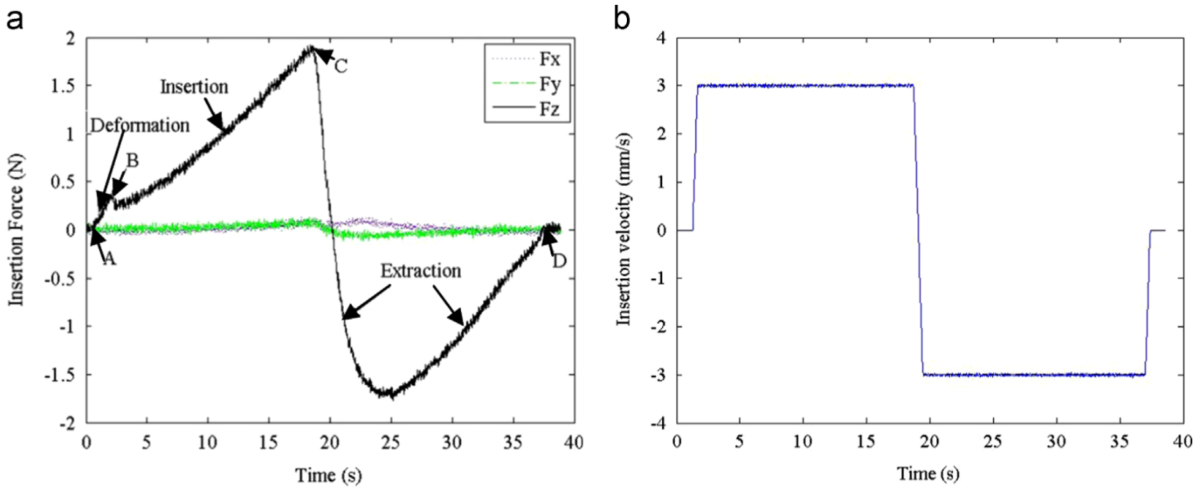

Figure 8: Force Profile of Needle-Tissue interaction Forces at 3 mm/s [22]

The force is seen reaching an initial peak when it maximally deforms the skin then drops off once the skin is pierced, followed by a relatively linear increase in force. This information is very useful for novice nurses since it can give them a better understanding of the dynamics they will experience. This data can also be useful in correlating force to required velocity, “Mahvash and Dupont (2010) showed that increasing the velocity of needle insertion will reduce the force of rupture event when it increases the energy release rate” [22] which can be seen in these graphs:

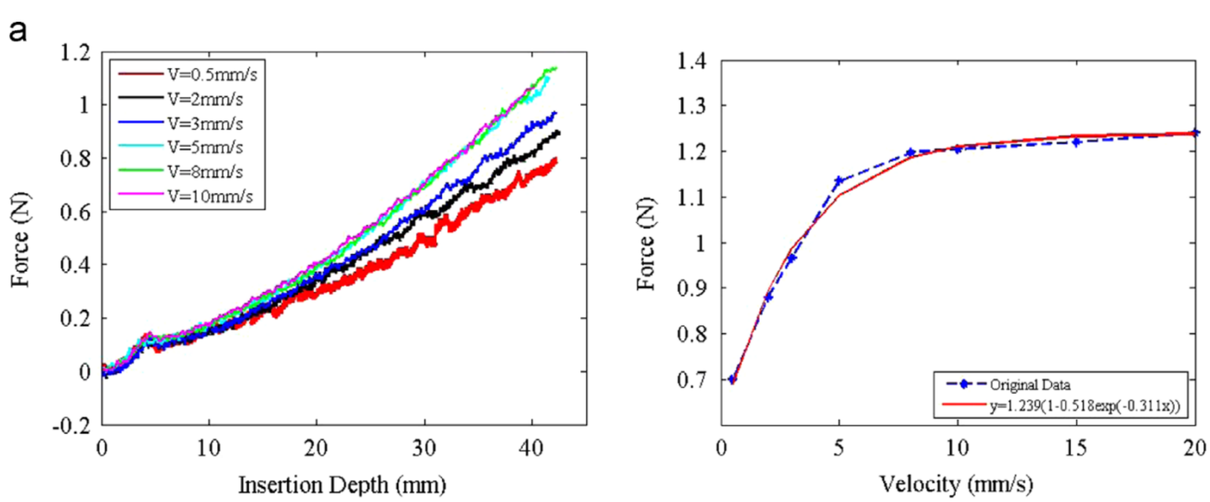

Figure 9: Force vs Insertion Depth and Velocity [22]

This velocity also becomes more critical once the needle has pierced the skin, since there is a higher likelihood of injury or irritation. Jiang et al. say that velocity and the "insertion process (interrupted and continuous)" greatly impact the insertion force.

Experimental Injection Training Methods

Research aiming to study the effectiveness of injection training has been limited to hands-off learning. A 2018 study compared the knowledge retained by 2 groups of nursing students after an experimental group was taken through a video presentation on subcutaneous injections while the control group received a 30 minute face to face lecture. Vicdan reported, "the score of the experimental group was 10 points… and the score of the control group was 11.98" [7] meaning the face to face lecture was a more effective teaching method. A 2021 study was able to test out a more immersive learning experience by presenting learning material about IM, SC, and IV administrations in Augmented Reality (AR) through games and animations. The material covered injection sites, angle, and tool preparation. Kurt and Ozturk concluded that, "MAR applications reduced their fears about injection practices, increased their motivation and self-confidence, provided a solid, clear picture of the subject, and facilitated the identification of the injection areas and applications, resulting in an efficient laboratory process" [8]. The results of these 2 studies show that more immersive hands-on learning experiences produce more knowledgeable and skillful students in this practice. Making a learning experience more engaging has great benefits for the student.

Motivation

The current background and state of injection practice has been outlined. Injection training instruction, guidelines, and practices are generally inconsistent. The severe lack of kinematic data of body parts and syringes during injection administration limits the conclusions that can be drawn about the practice and would be useful for many applications. Injections are also procedures that require precision and take time and effective training to execute correctly. Hands-on training has proven to be a superior method for nursing education. To this end, it has been hypothesized that kinematic parameter data would be useful for feedback to those learning how to administer injections, and published kinematic data on the procedure would prove conducive to progress. This motivates the purpose of the research that follows, to develop a user friendly, cost effective, and accurate motion capture system, that can give a nurse performing an injection procedure real time feedback on injection kinematics.

Methodology

To make a proof of concept system, a goal was set to capture 3 key performance indicators (KPIs) of the injection. These were injection velocity, injection rate, and injection angle. The system would be tested on one of the most common injection types, an intramuscular injection into the shoulder/deltoid of the patient using a 1 ml syringe and 0.5 ml medication volume. The system will need to capture the “approach” or the dart-like motion of moving the needle toward the skin, the needle contact, and the medication “administration” or the compressing of the plunger.

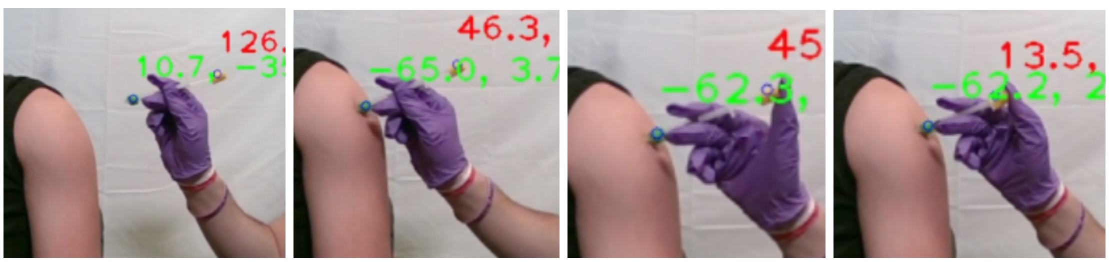

Figure 10: IM Deltoid Injection Stages: Approach, Needle Contact, Start Administration, End Administration

The first motion capture method that was considered for this research was the state of the art, passive, marker-based system. This traditional approach involves placing reflective markers on specific body joints or objects and using multiple cameras to track their positions in 3D space. The data captured by these markers is then used to animate virtual models to analyze their movement.

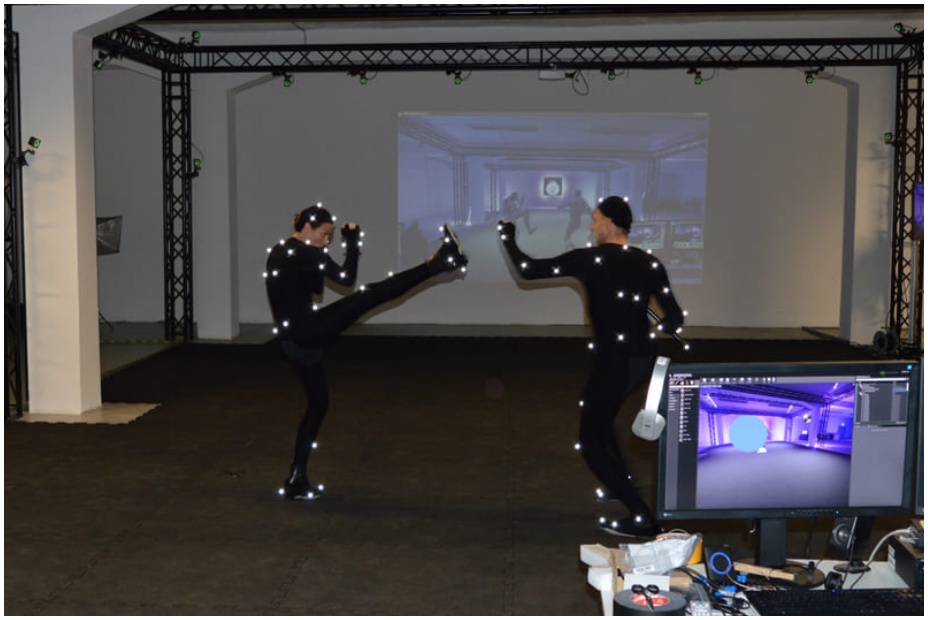

Figure 11: Marker-Based Motion Capture System [27]

Marker-based systems offer high accuracy but require a controlled environment and can be time-consuming. To collect data markers must be precisely placed on the body and objects of interest and calibrated for scaling purposes. The data collected must also be labeled and gap filled on one software, for example, Qualysis, then exported in a different file format to be processed in a separate inverse kinematics software such as OpenSim. This pipeline would be extremely difficult to automate in order to make the system real time and user friendly. Additionally, entire marker-based systems are expensive and not portable. For nursing students to use this system they would have to conduct the injection training in a low fidelity motion capture lab. For these reasons, more accessible and cost effective methods of motion capture were explored.

Open Source Computer Vision (OpenCV) frameworks were considered next for this application. These frameworks leverage machine learning algorithms to identify objects, body parts, and other features in a video stream and estimate their location frame by frame, eliminating the need for markers. “MediaPipe” offers some of the best skeletal tracking models for computer vision, 2 of which could be useful for this application. Their “Hand landmark” detection and “Pose landmark” detection could be used to detect the hands of a nurse administering an injection and the arm of the patient, respectively.

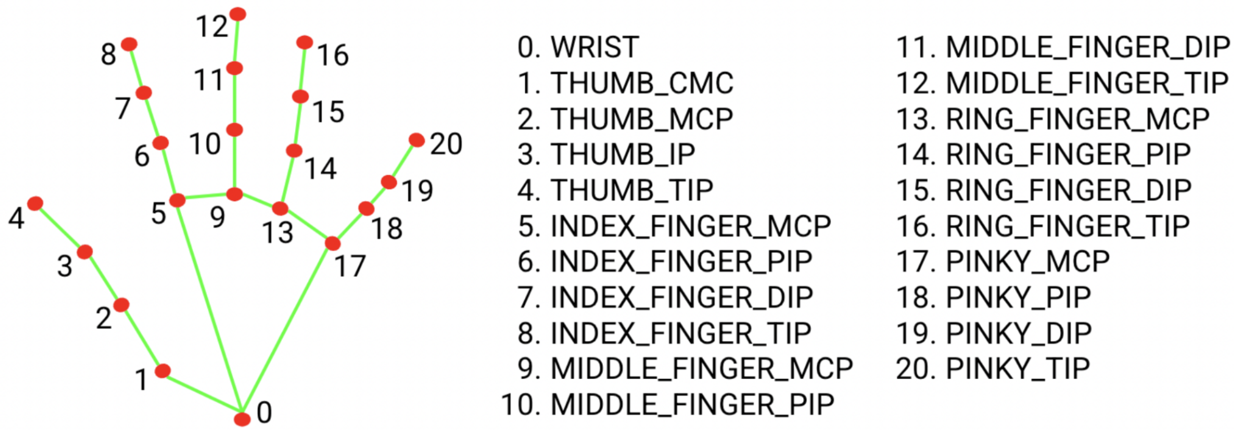

Figure 12: MediaPipe Hand Landmark Detection Documentation

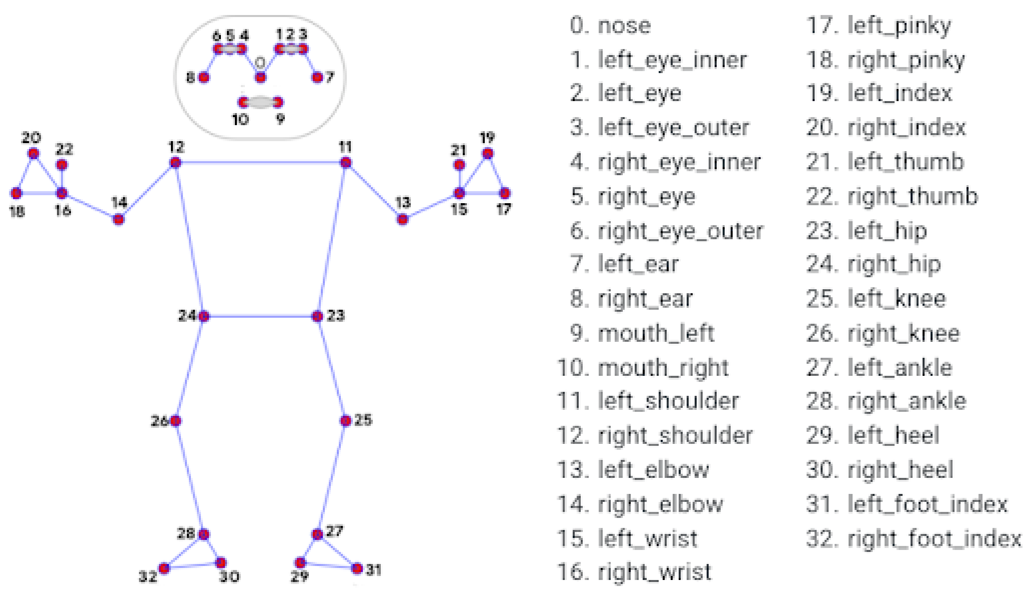

Figure 13: MediaPipe Pose Landmark Detection Documentation

The figures show all the landmarks each model can identify and output an estimated location for. Multiple landmarks can even be called upon in conjunction with each other to output joint angles. The issue is, currently, these cannot be run simultaneously on the same inputted video stream to track both the nurse's hands and the patient's pose. To bypass this, another OpenCV object detection model could be used to identify the nurse and patient in each frame, their bounding boxes could then be cropped from the frame and each inputted into their respective MediaPipe landmarking tracking models. The results of this using the "YOLOv3" object detection model can be seen below:

Figure 14: Running Respective Landmark Models on Cropped Images

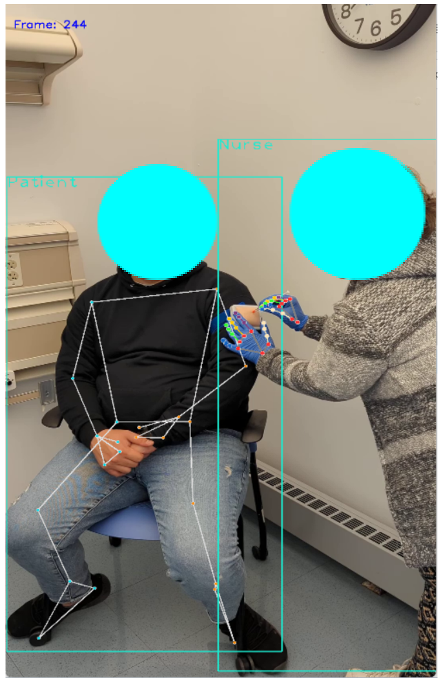

Figure 15: Combined MidiaPipe Landmark Tracking

This system was run first on an injection demonstration video posted by “Medical Assistants - At the Heart of Healthcare” youtube channel. Primary videos simulating an intramuscular injection were then taken at different framings (close up and wide shot). The downsides of this system include a long video processing time, inadequate accuracy, and poor tracking consistency. Additionally, because only hand landmarks can be tracked, the true location and orientation of the syringe can only be estimated, theoretically, and only for portions of the injection procedure since hand position changes relative to syringe position. This motivates the next and final motion capture method.

This method uses a “Intel RealSense D455 Depth Camera” to record the injection procedure at 30 Hz. Colored markers were placed on either end of the syringe, one on the needle end (with the needle removed) and the other on the end of the plunger, giving the position and orientation of the syringe for each frame. By placing one marker on the plunger, the relative distance between the markers could be tracked to measure injection rate or the speed at which the plunger is compressed. A custom script locates the pixel coordinates (x & y) of the color markers based on their HSV value which has been calibrated. The depth (z) information in (mm) of these coordinates is then acquired from the camera's depth frame and also used to normalize the x and y coordinates to (mm). The HSV value range for the shoulder of the patient is also calibrated so the shoulder contour can be identified within a defined area on the video stream. The script identifies 3 points within that contour, used to define the plane of the shoulder, this is then used to calculate injection angle. A white backdrop was placed behind the subjects to control the colors captured in the video stream and an LED Soft Light Panel was placed behind the camera, directed towards the subjects in order to control light and color as well. The full system is shown below and costs about $550.00.

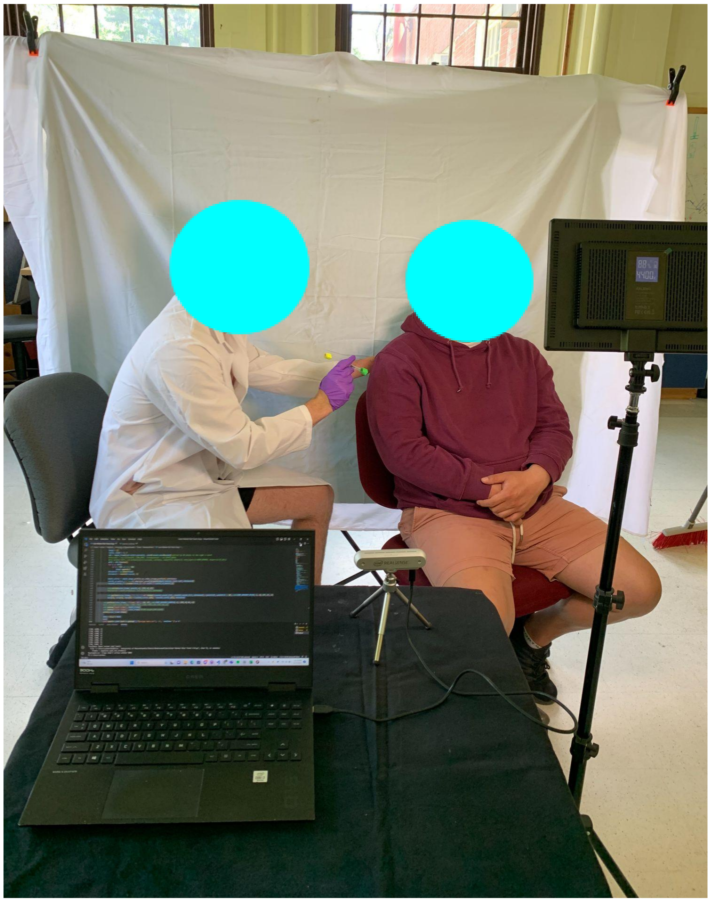

Figure 16: Depth Camera Motion Capture System

Data was collected of a simulated intramuscular injection into the shoulder of a patient using a 1 ml syringe with the needle removed and the medication volume set to 0.5 ml. The objective of the data collected was purely to measure the capabilities of the system, so proper technique was not a priority. A script was first run to capture the shoulder plane of the "patient", in which 4 "snapshots" of the shoulder plane were taken to then be averaged in post processing.

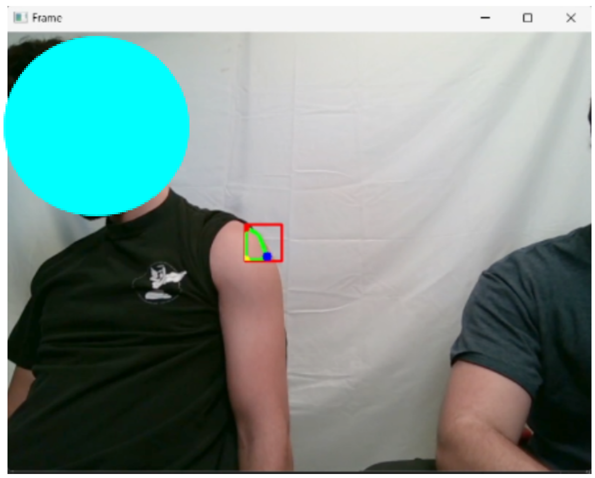

Figure 17: Capturing Shoulder Plane

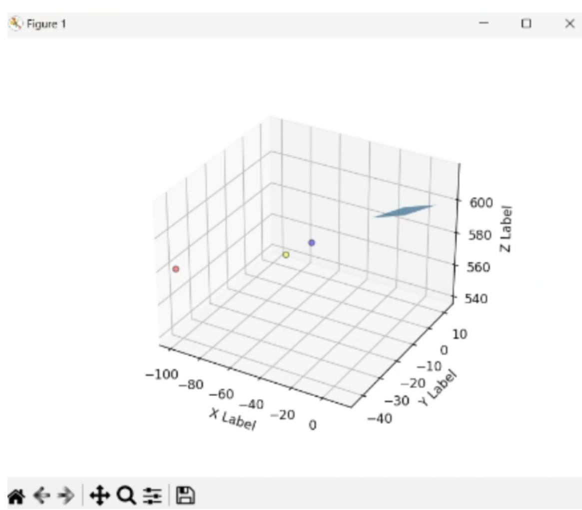

Figure 18: Captured Plane Plotted

After the shoulder was captured, a second script was run which would track the location of the color markers on the syringe. The syringe was brought into the frame by the "nurse" and an “simulated” intramuscular injection was performed into the shoulder. “Simulated” in this context meaning no needle was inserted into the skin nor was any medication administered, but the motions were executed as if they were. This can be seen below:

Figure 19: Capturing Needle Position During Injection

The “patient” was instructed not to move their arm between shoulder plane capture and the simulated injection. Data was collected on four separate injections into the shoulder. The data collected could then be used to calculate the angle(s) between the syringe and the shoulder plane at different times during the injection as well as the injection velocity and injection rate. Similar to other traditional motion capture methods, the motion of the syringe relative to the shoulder could be animated virtually.

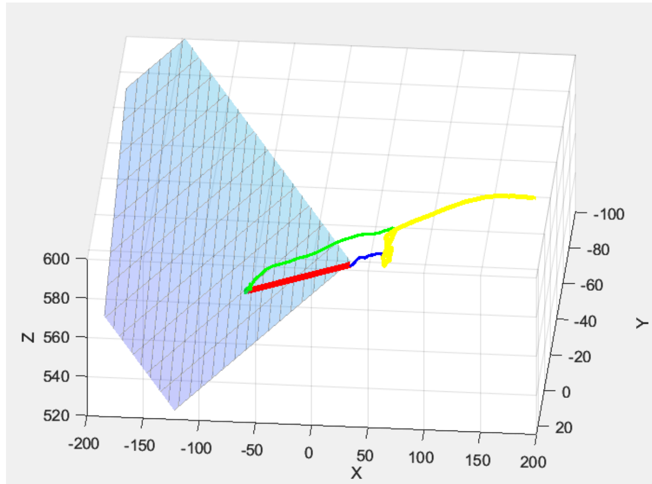

Figure 20: Syringe Path Relative to Shoulder Plane Matplot Animation

In **Figure 20** above, the red line represents the syringe with the green and yellow lines tracking the path taken by the needle tip of the syringe and the plunger, respectively. The blue line tracks the path of the plunger while it is being compressed and the blue plane represents the shoulder of the patient.

An injection angle accuracy test was also conducted on this system. Using a custom fixture, the syringe could be mounted at a specific angle relative to a surface which simulates the shoulder of a patient. The syringe could slide within the fixture while keeping its orientation relative to the shoulder surface consistent. Position data of the syringe and shoulder surface were collected using the aforementioned method, changing the orientation of the syringe to the shoulder surface and the shoulder surface to the camera in different trials. This can be visualized below.

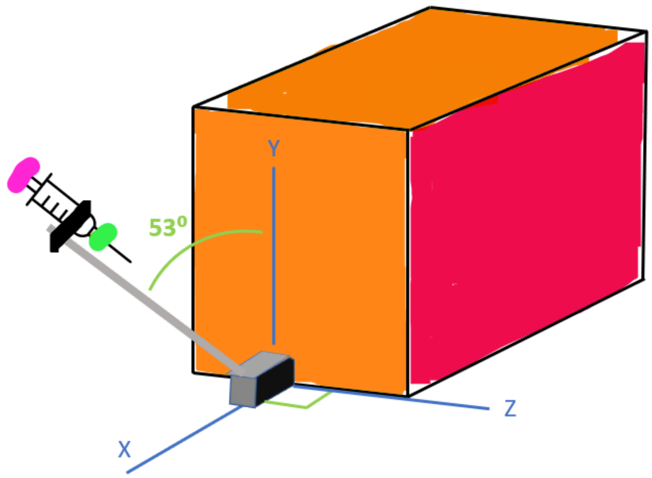

Figure 21: Isometric View of Test Fixture

The syringe is shown at a 90° angle about the Y axis and a 53° angle about the Z axis to the shoulder surface. The syringe's angle about the Y axis will change from trial to trial but its angle about the Z axis remains the same for all trials, assuming the Z axis remains normal to the syringe's 2D vector from a top view.

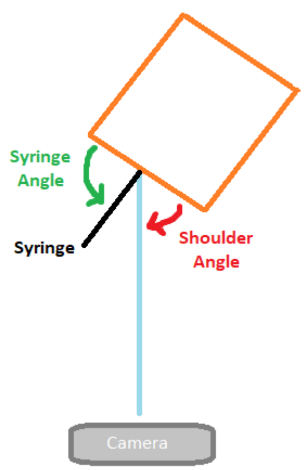

Figure 22: Top View of Test Fixture to Camera

The syringe was kept at a 90° angle about the Y axis for the first 4 trials in which the shoulder angles were set to 67.7°, 45°, 22.5°, and 0°, relative to the camera about the Y axis (reference

Figure 35). Then, keeping the shoulder angle consistent at 0° to the camera, the syringe angle relative to the shoulder surface about the Y axis was set to 45°, 90°, and 135°, for 3 separate trials (reference **Figure 42**). A tolerance of ± 5 degrees of error was for these tests, as that difference will not change the outcome of an intramuscular injection (refer to **Figure 2**).

Results & Discussion

Tracking consistency, that is the percentage of frames in which the system was able to detect coordinates of a desired landmark, and accuracy of the tracking, or how close the virtual landmarks are to the actual body part, were both examined. Using the OpenCV framework system to capture landmark data on an injection demonstration provided by “Medical Assistants - At the Heart of Healthcare” youtube channel tracked the shoulder/arm position of the patient with 77.2% consistency, but with poor accuracy as can be seen in **Figure 23** below.

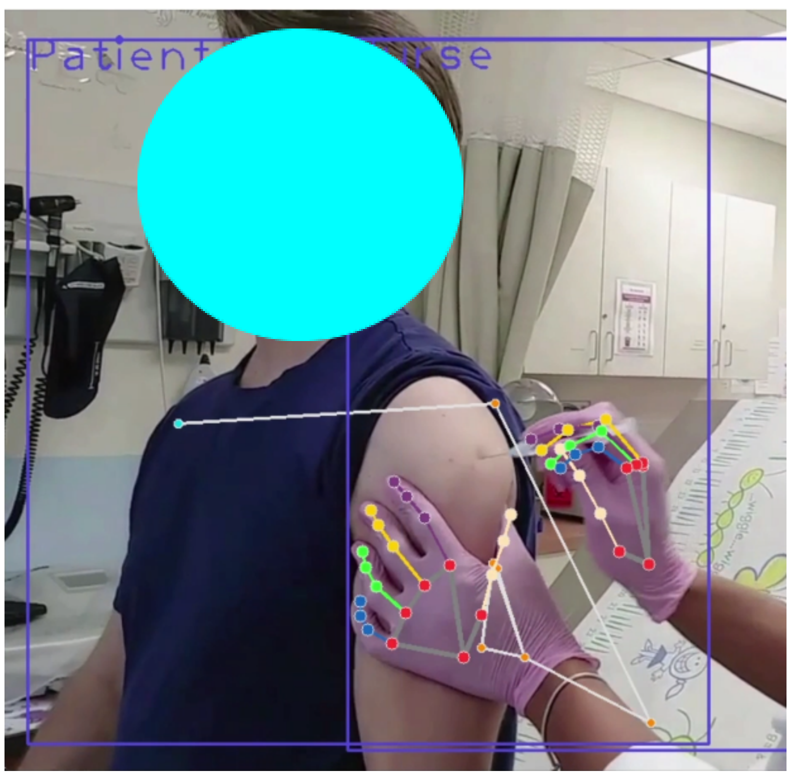

Figure 23: OpenCV Landmark Tracking on Injection Demonstration

While landmarks for the left shoulder and elbow of the patient were drawn and recorded, they were rarely accurate as seen in **Figure 23**. This cannot be quantified but the inaccuracy was so apparent that the shoulder data recorded could be dismissed. This inaccuracy can be attributed to the framing of the video. Since MediaPipe Pose is primarily trained on images of a full body, it has trouble recognizing key landmarks when only a portion of a body is seen. The hand landmarks were tracked with 46.5% consistency but were visibly more accurate. The video was not ideal though, due to the framing and non stationary recording. For these reasons videos were recorded on a smartphone secured to a stand of a simulated injection. Snapshots of these videos pictured in **Figures 13 & 14** show a wider framing, capturing the patient's entire body. Pose tracking consistency dropped to 16.8% but increased visibly in accuracy, giving an upper arm segment that was closer to the true arm position of the patient. This was favorable since the position of the patient did not change considerably. Hand tracking consistency improved to 79% and was not noticeably more or less accurate. This was favorable as the hands are constantly moving. The motion of the "wrist" landmark (refer to **Figure 11**) on the hand holding the syringe was tracked and plotted along with the shoulder position of the patient. This can be visualized below in **Figure 24**, with the blue line representing the wrist trajectory during the "approach" of the injection and the orange line representing the patient's upper arm segment (shoulder to elbow). The wrist data was passed through a 5 frame moving average filter.

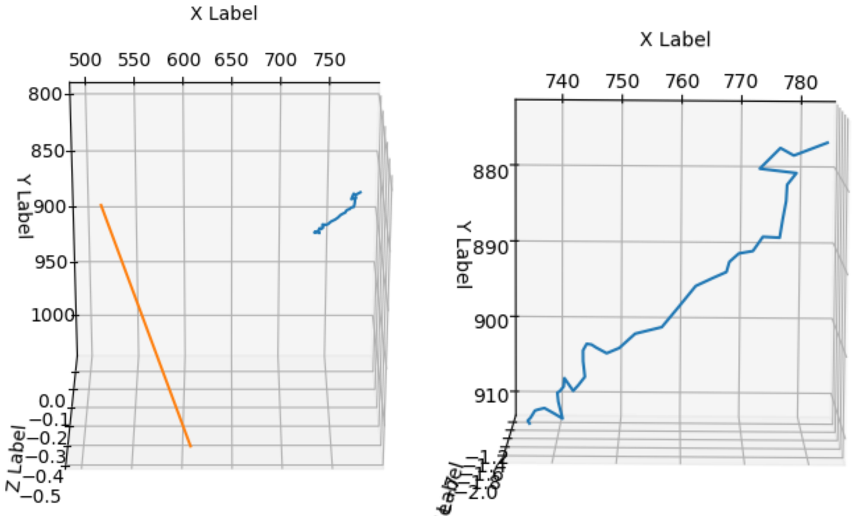

Figure 24: Left: Wrist Trajectory & Arm Position , Right: Zoomed in Wrist Trajectory

Using the data collected, the average velocity of the wrist during the approach was calculated to be 4.4 mm/s. This wrist trajectory information can give a general idea of how the syringe moves relative to the patient's arm, but does not give the full resolution picture of the syringe's kinematics. Since the orientation of the syringe is unknown, the injection angle can not be quantified. Furthermore, the quality and accuracy of the data is in question. Not only does the data come with a lot of noise, but it is 1 dimensional in the xz plane.

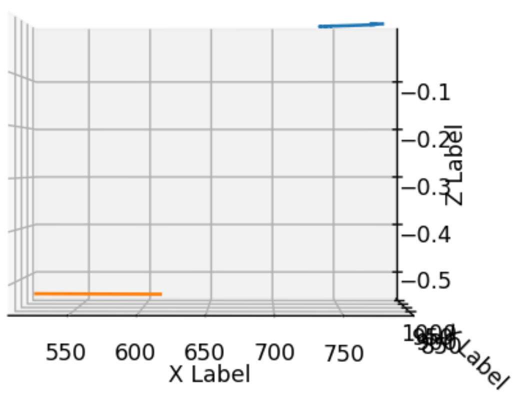

Figure 25: Top View of Wrist Trajectory & Arm Position During Approach

It can be seen in **Figure 25** that MediaPipe can detect landmarks at different depths, but assumes they remain at that depth or only exist in the xy plane at that depth. Similarly to how the wrist landmark was tracked, the thumb landmark was also tracked and plotted during "administration" to measure injection rate.

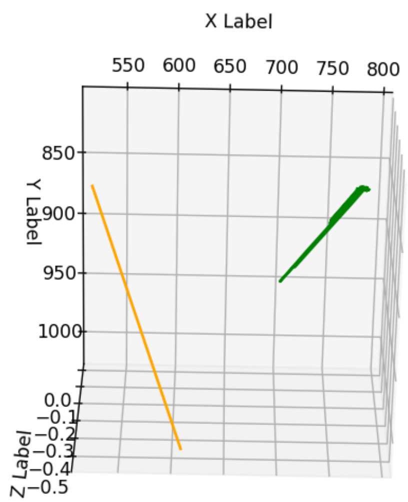

Figure 26: Thumb Trajectory & Arm Position During Administration

The injection rate was calculated to be 15 mm/sec, giving a rough estimate of how fast the plunger was compressed.

The depth camera system was able to capture syringe coordinate data or detect the color markers on either end of the syringe with minimum 98.4% consistency and sub-millimeter accuracy.

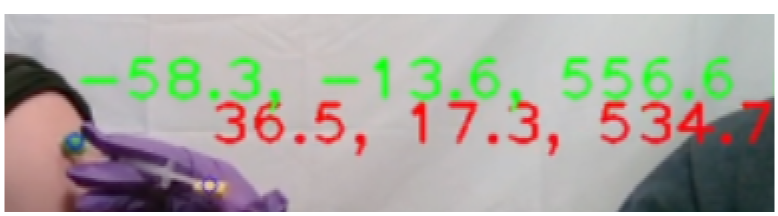

Figure 27: Real Time Detection of Color Markers 3D Coordinates

The system can track in real time with pinpoint accuracy and lower noise level. The 1.6% of lost tracking can largely be attributed to the small portion of time when the syringe enters and exits the frame. This data was used to plot the instantaneous velocity of the syringe during the "approach" seen below in **Figure 28.**

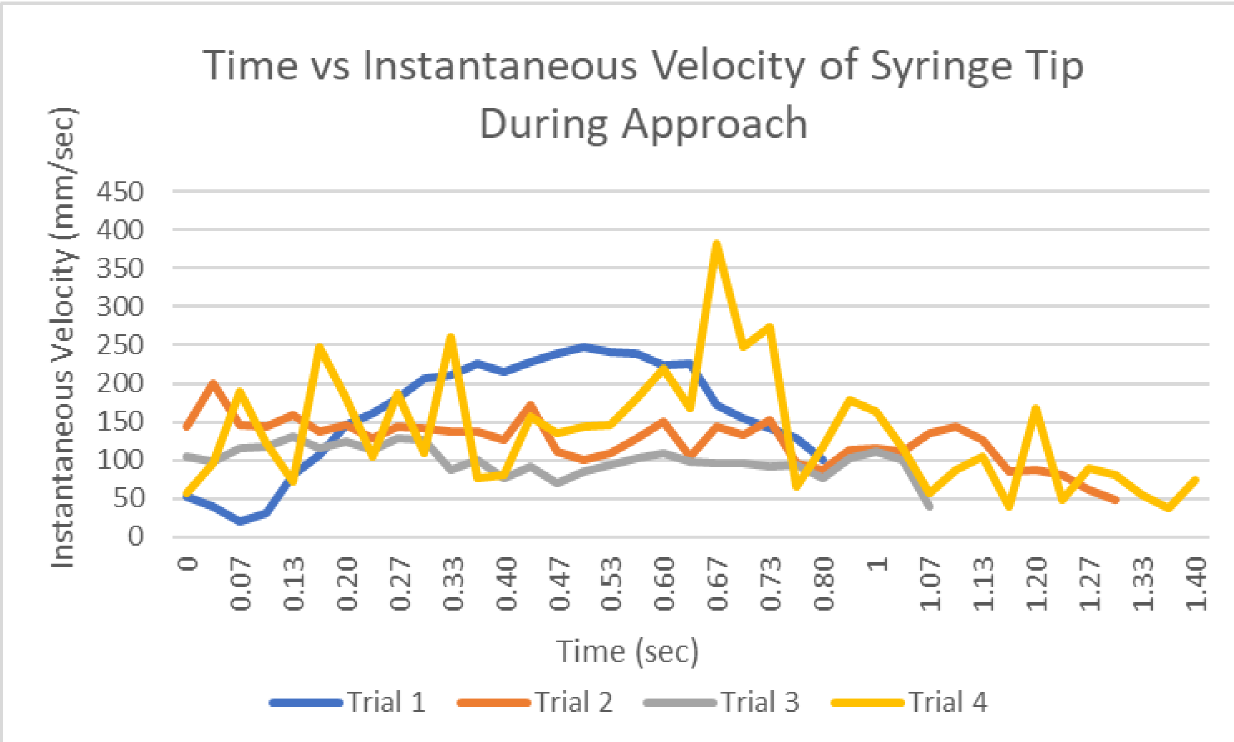

Figure 28

The data had considerable noise and was passed through a 5 frame moving average (MA) filter.

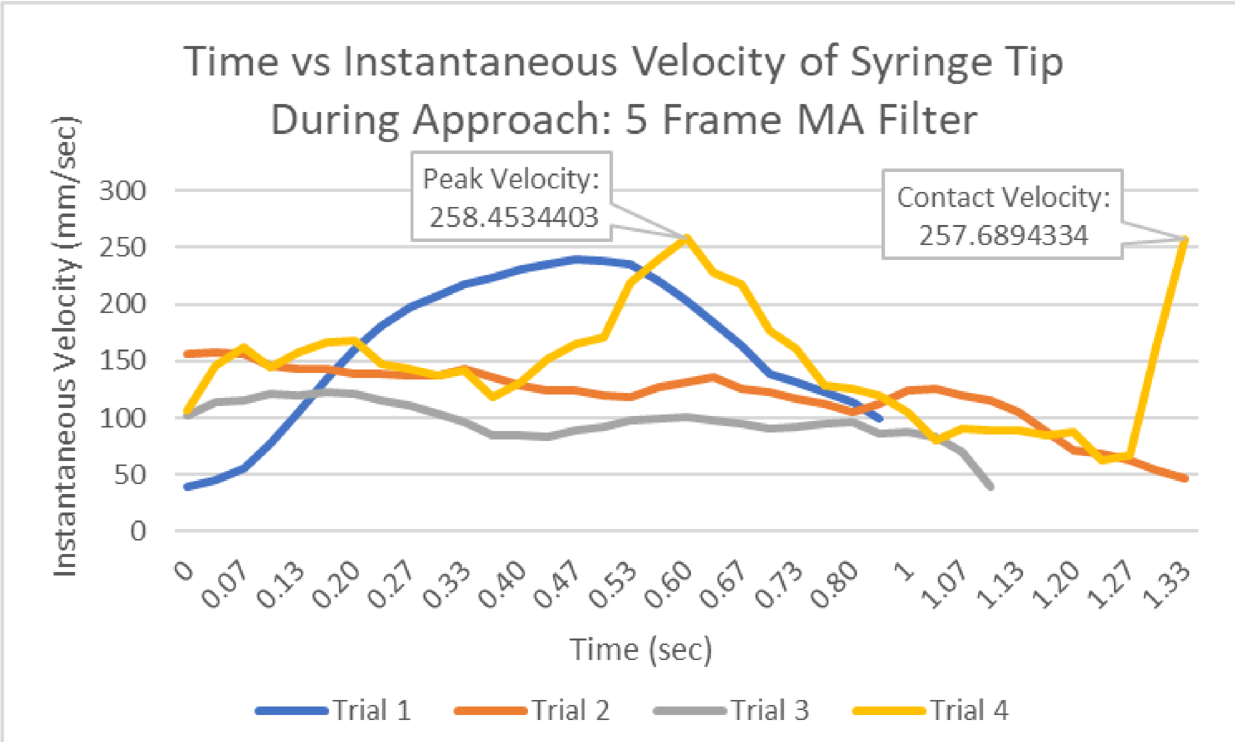

Figure 29

The velocity appears to peak at the beginning of and in the middle of the approach. The average velocity of trials 1, 2, 3, and 4 were 150 mm/sec, 115 mm/sec, 100 mm/sec, and 50 mm/sec, respectively. By selecting specific points seen on the plot, metrics such as "peak velocity" and "contact velocity" can be compared to the same metrics from the Katsma and Smith study [5]. This allows for a high resolution of the velocity profile, being the instantaneous velocity at different points of interest during the injection. Similar to velocity of the entire syringe, the instantaneous velocity of the plunger during "administration" was also recorded and plotted below for the 4 trials.

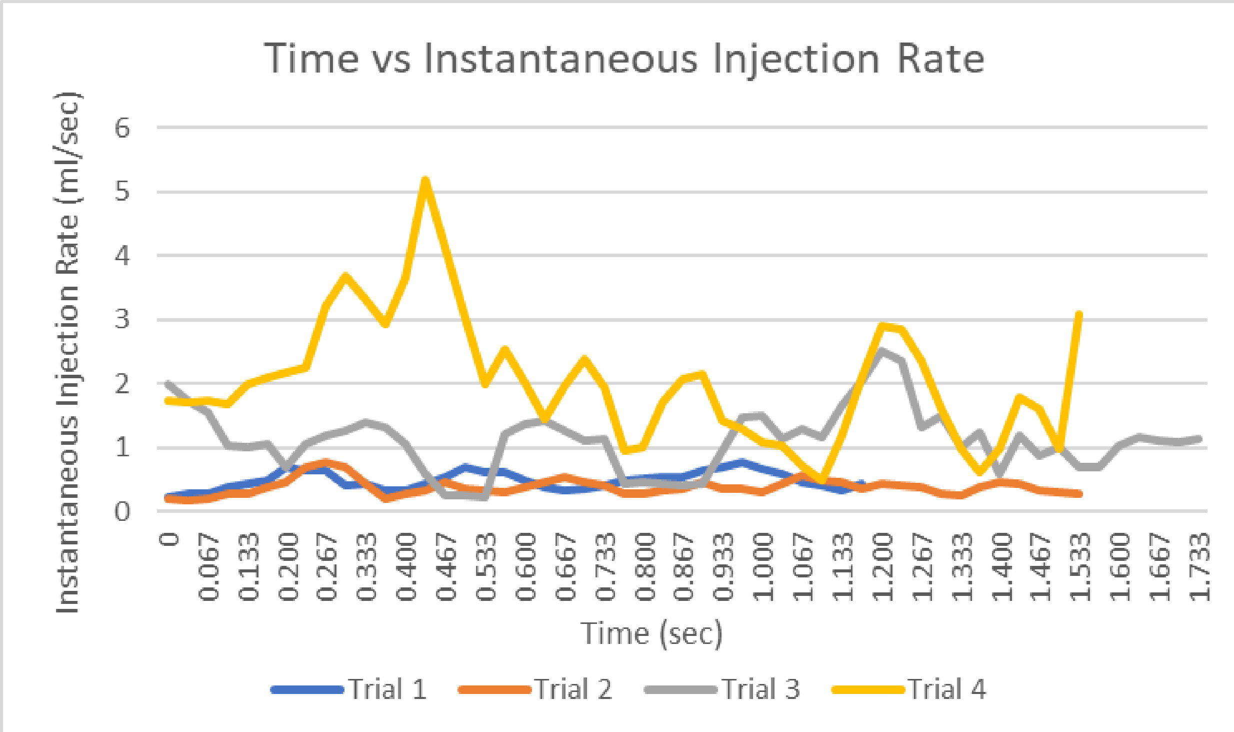

Figure 30

Trial 4 had considerably more noise than others so the raw data was passed through a 5 frame MA filter before deriving instantaneous velocity. After plotting the noise was further suppressed by passing the velocity data of all the trials through a 5 frame MA filter, resulting in **Figure 31.**

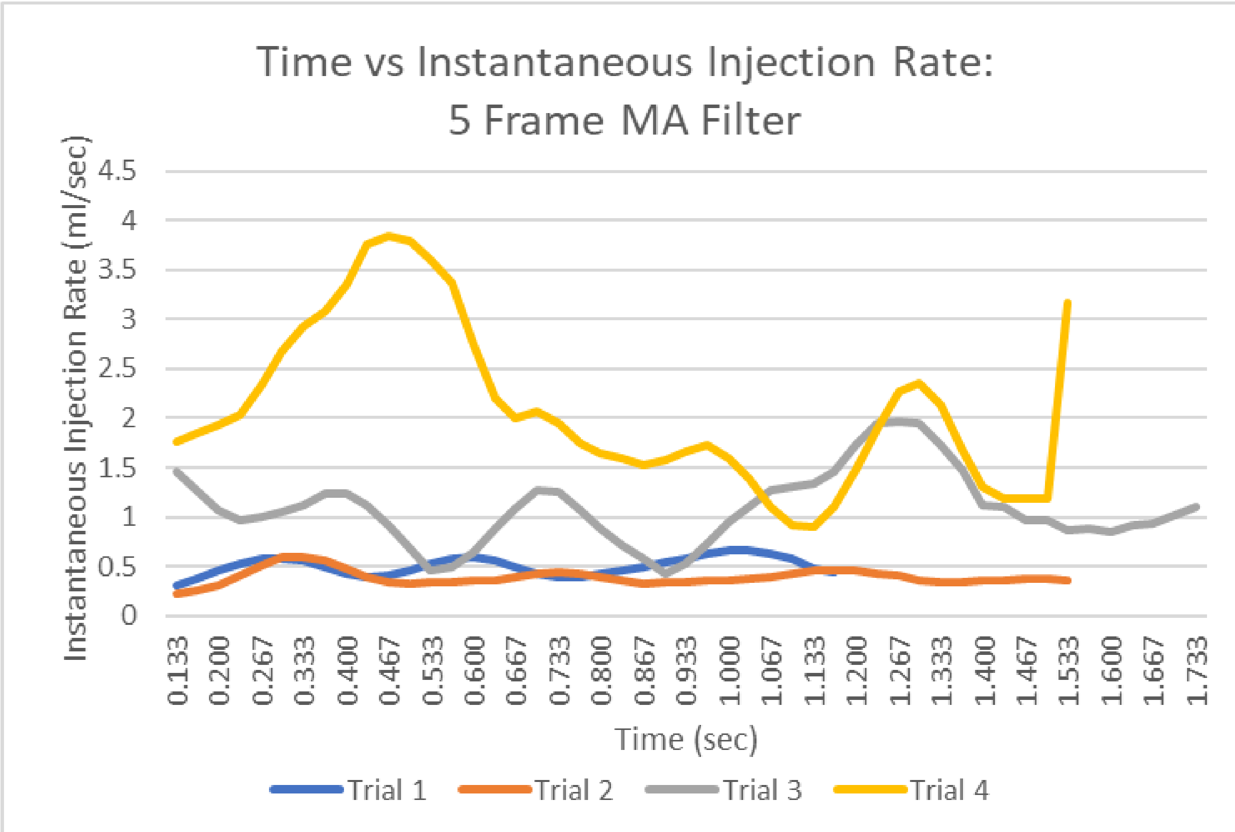

Figure 31

The average injection rates of trials 1, 2, 3, and 4 were 0.377 ml/sec, 204 ml/sec, 0.191 ml/sec, and 0.193 ml/sec, respectively.

Lastly, the injection angle(s) were calculated from each trial and plotted vs time. The main injection angle of interest will be referred to as the "Minimum Normal Angle" which can best be explained by **Figure 32**.

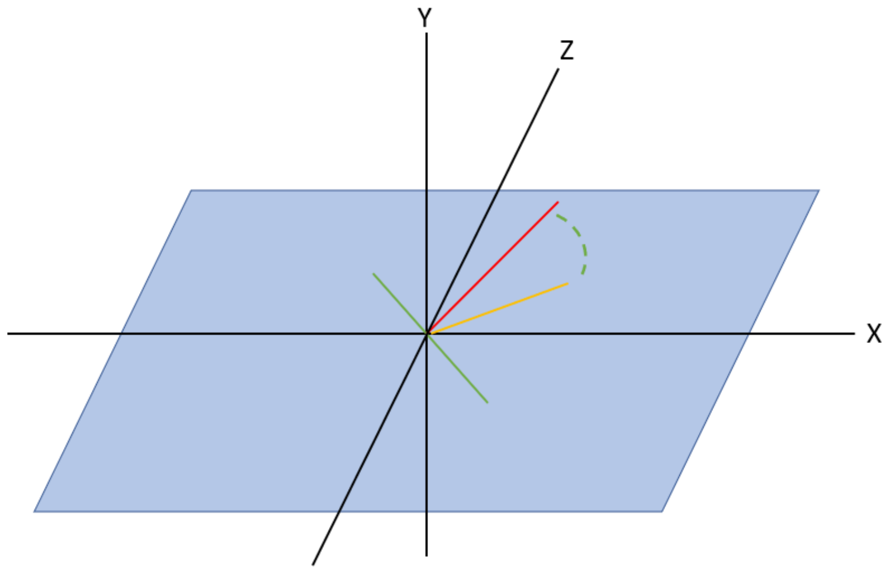

Figure 32: Minimum Normal Injection Angle Diagram

The minimum normal angle is represented by the green dotted line in the figure, which is the angle of the red line (representing the syringe) to the blue plane, about the green line or axis. The yellow line is the projected syringe vector on the x-z plane (representing the shoulder plane). The green axis is defined as the vector on the shoulder plane, normal to said projected yellow line, and the minimum normal vector will always be found about this green axis. The system finds this angle by solving for theta in **Equation 1**, S being the syringe vector and N being the shoulder plane normal vector.

Equation 1: $cos(\theta) = (S \cdot N)/(|S| * |N|)$

The syringe angle about the camera's x, y, and z axes can also be calculated by projecting the 3D vectors in 2D planes, and solving for theta in the same equation. For example, to find the angle about the Y axis, the vectors are defined in the form (x, 0, z). **Figure 33** plots the minimum normal angle as well as the angle about the x, y, and z axes which the syringe makes with the shoulder plane in trial 1.

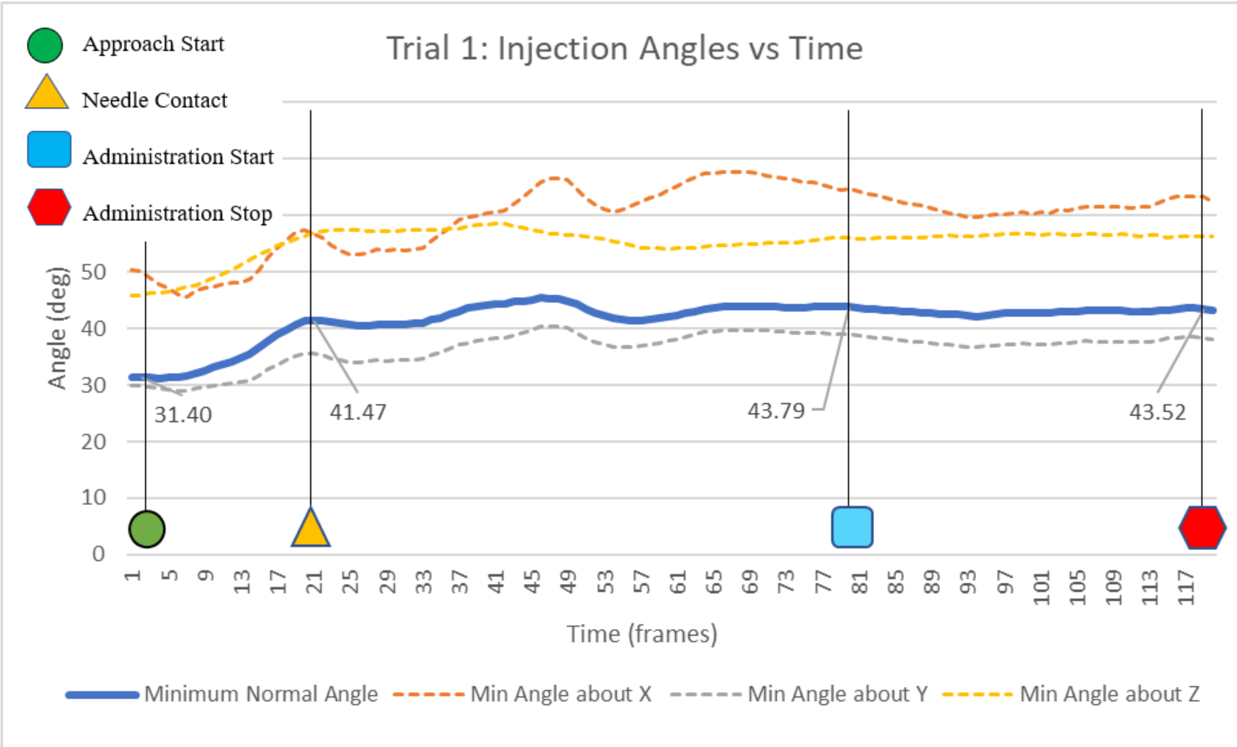

Figure 33

This gives even more information about the injection angle than the Katsma and Smith study [5]. This is plotted versus time to gain understanding of how the syringe changes in orientation depending on what the stage of the procedure is, which are indicated by the green, yello, blue, and red markers. The minimum normal angle from each trial was also plotted against one another in **Figure 34.**

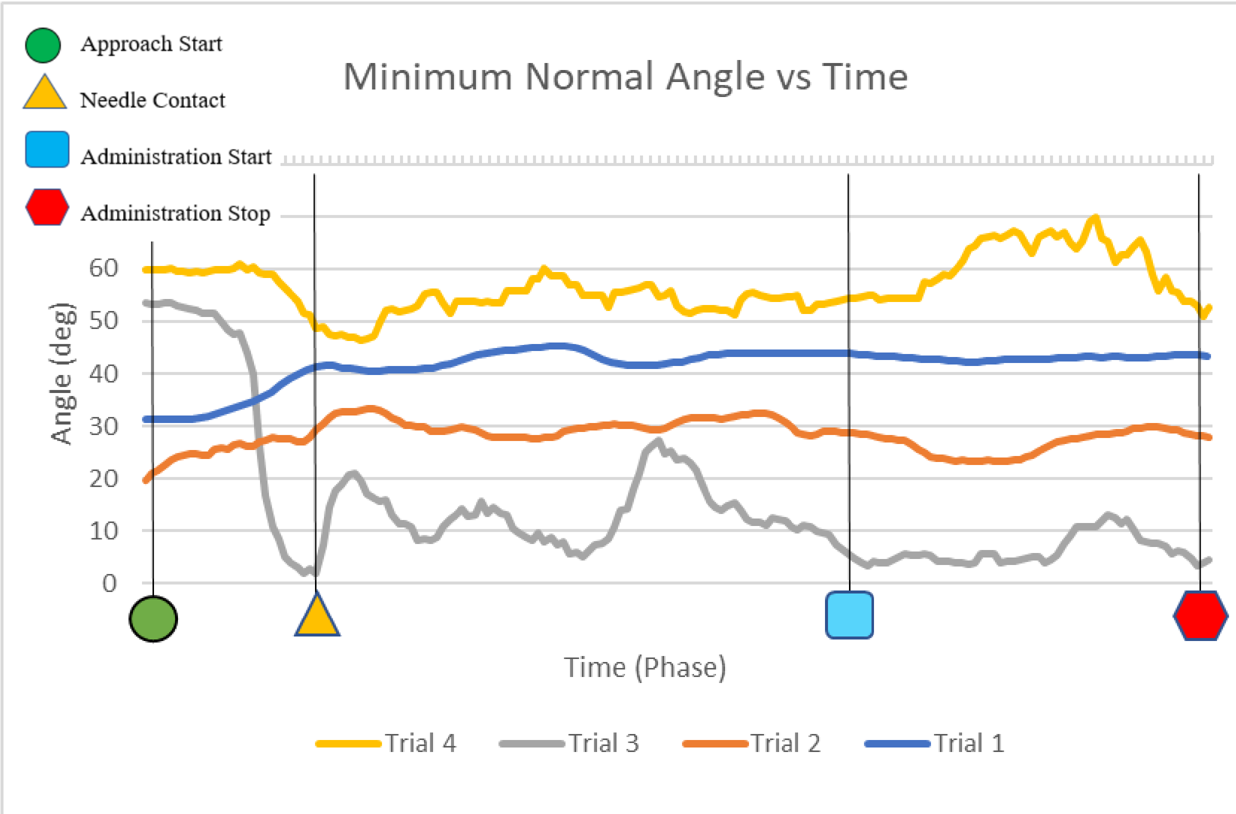

Figure 34

For the most part all the trials have the largest change in angle during the approach, have a "shaky" behavior between needle contact and the start of administration while the hand is readjusting its position, then the angles stay the most consistent during administration. This information could lend key insights into injection administration errors.

Results of the angle accuracy test described in **Figure 21** are presented below. The first of the two controlled tests keeps the angle of the syringe to the shoulder surface constant at 90 degrees while changing the angle between the shoulder surface and the camera's line a view. This can be visualized in **Figure 35.**

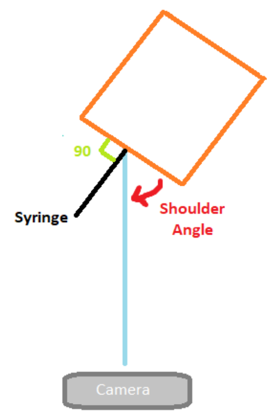

Figure 35: Angle Accuracy Test 1

The error in degrees of the angle about the Y axis was plotted for each shoulder angle, and a polynomial line of best fit was plotted and its equation given.

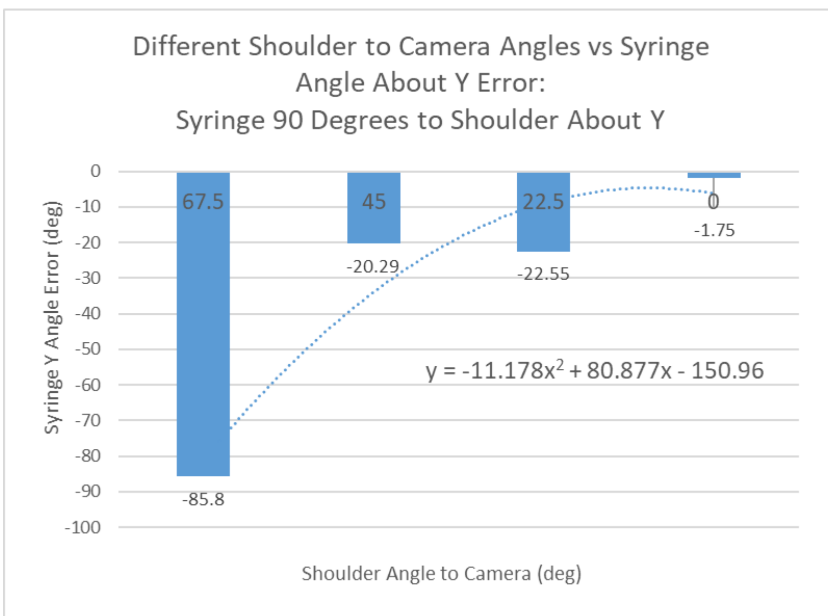

Figure 36

The shoulder to camera angle of 67.5 degrees had a massive error due to an error in data collection. It is believed that the position of the syringe interfered with the distance measurement of the shoulder plane. This error bar was removed in the next plot to get a more accurate polynomial trendline equation for the error.

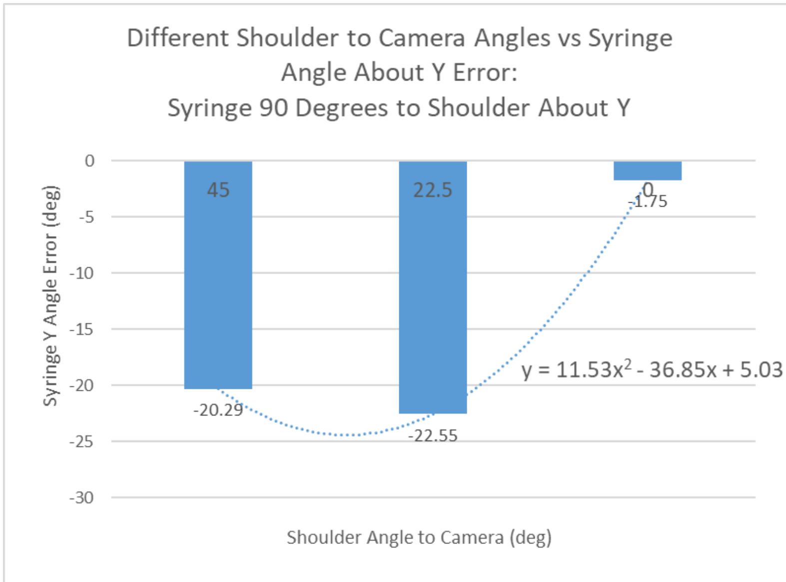

Figure 37

Some of this error is due to the syringe detection and some is due to the shoulder plane detection. In the next plot, the true shoulder plane was hard coded into the angle calculation, resulting in the following error bar graph, which accounts for purely syringe detection error.

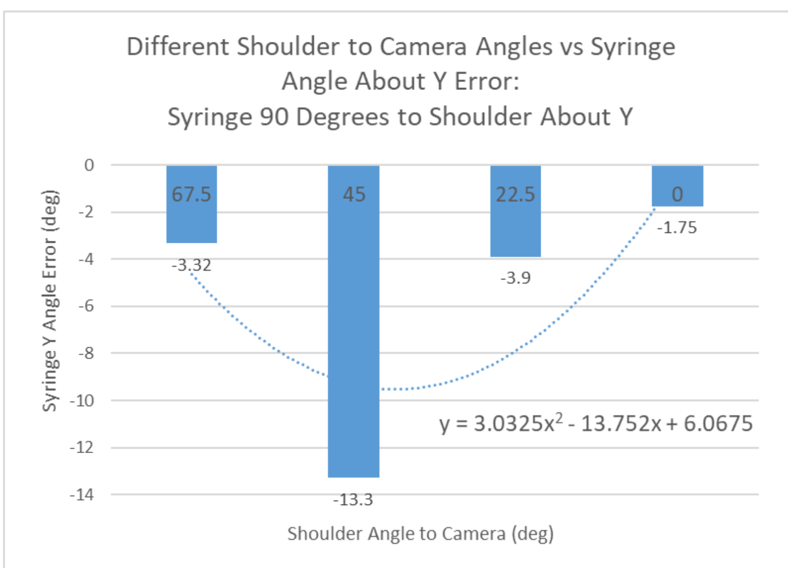

Figure 38

This dramatically lowers the error at all orientations except for 0 since it was already calculated using this method. The 45 degree shoulder to camera angle produces the largest error of 13.3 degrees, while the rest are under 4 degrees, which is within the specified tolerance. It can be concluded that the shoulder plane measurement accounts for 96%, 34%, and 83% of the error for shoulder to camera angles of 67.5, 45, 22.5 degrees, respectively, when measuring the syringe angle about Y axis with this system.

The same errors were quantified for the minimum normal angle of the syringe, with an actual value of 53 degrees.

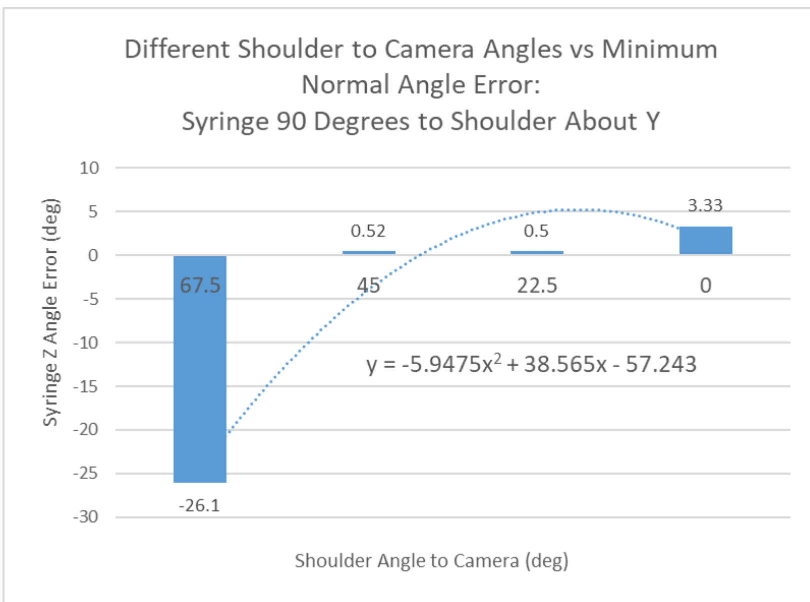

Figure 39

Again, a massive error is seen at the 67.7 degree orientation, which was removed in the next graph to provide a more accurate polynomial trendline equation.

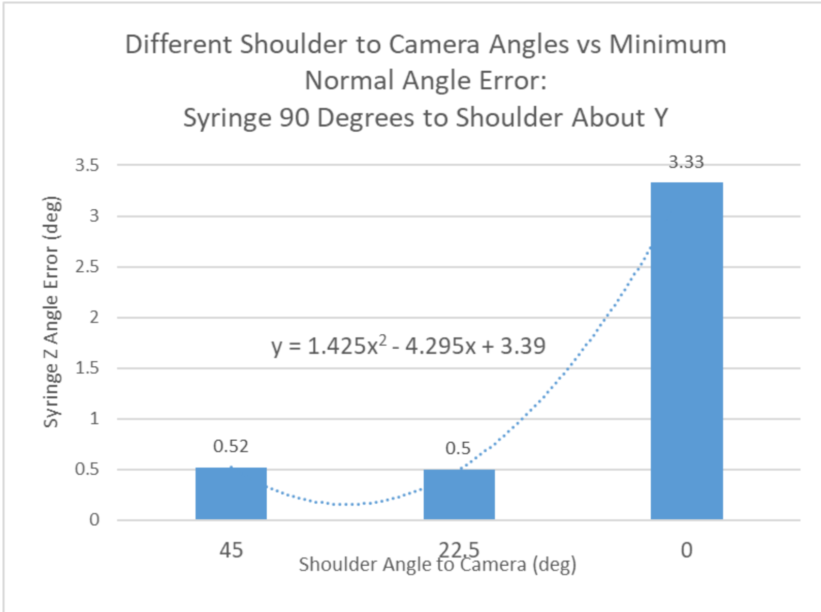

Figure 40

The errors for this angle are on average lower than the errors about the y axis. This is good news for the system as the normal angle is of greater interest. With the exception of the 67.5 degree shoulder to camera angle, all are within the tolerance. Hard coding the plane measurement to the actual orientation gives us the error plot below.

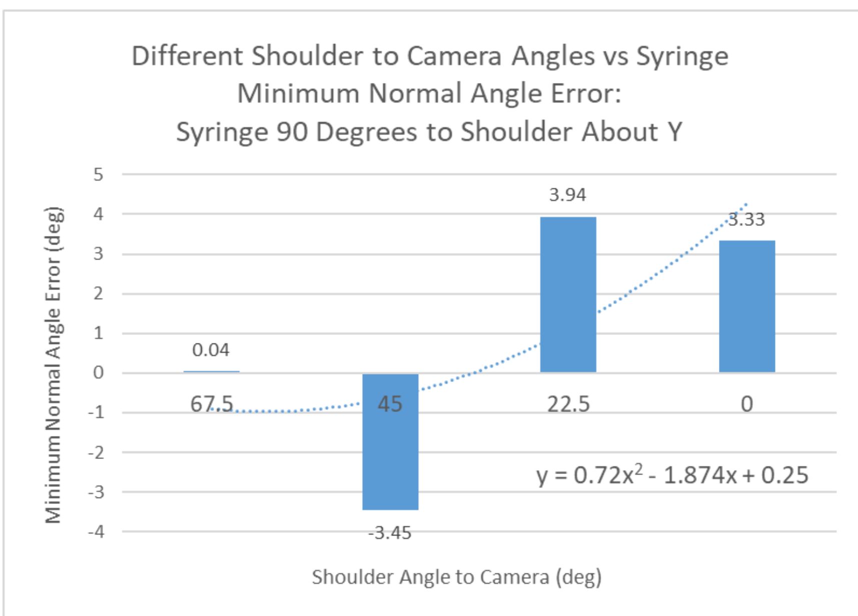

Figure 41

Figure 41 improves the error at 67.5 to nearly 0 but increases the error at 45 and 22.5 degree shoulder to camera angles, revealing the syringe and shoulder measurements had proportional errors at those orientations. Regardless, the errors are all within tolerance. It can be concluded that the shoulder plane measurement accounts for 98% of the error for the 67.5 degree shoulder to camera angle orientation when measuring the minimum normal syringe angle with this system. On the flip side, for 45 and 22.5 degree orientations, the shoulder plane measurement seems to scale the angle measurement to have less of an error.

The second accuracy test kept shoulder to camera angle constant, while changing the syringe to shoulder angle about the Y axis. For this test the shoulder plane was hard coded into the calculation, therefore the errors are a test of purely the syringe detection accuracy. **Figure 42** outlines this test.

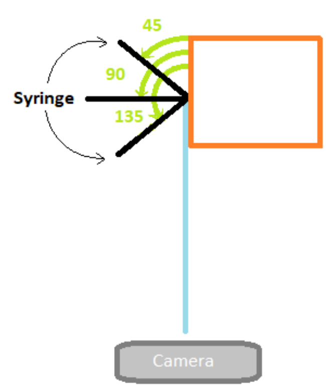

Figure 42: Angle Accuracy Test 2

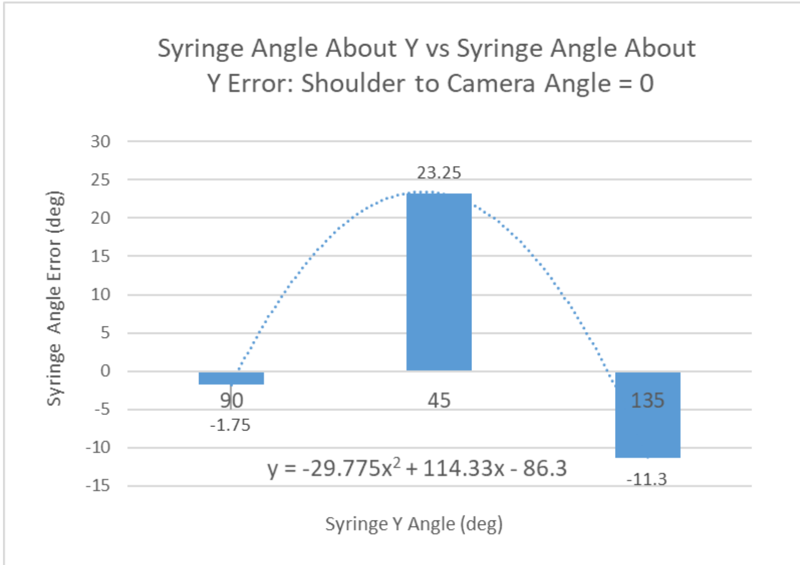

Figure 43

Only the syringe angle about Y at 90 degrees is within the tolerance for the data shown in **Figure 43**.

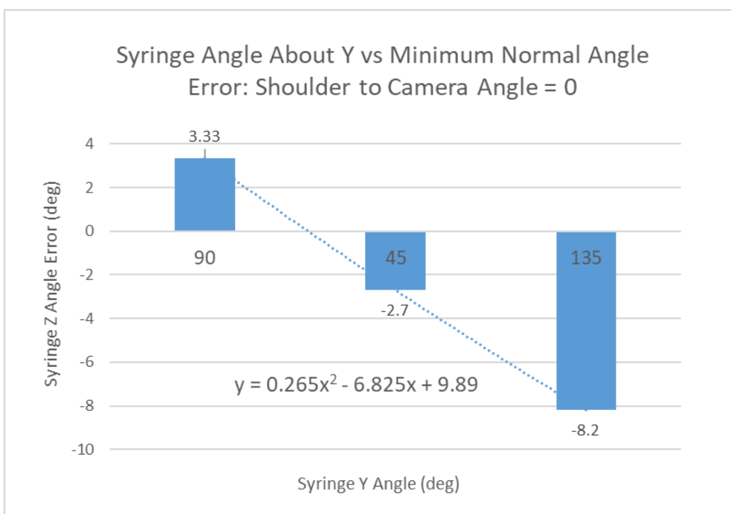

Figure 44

For the minimum normal syringe angle both 90 and 45 degree syringe angles are within the tolerance but 135 degrees is outside. The average error is lower for the minimum normal angle than for the angle about the Y axis, which is a positive for the system.

Bringing all this data together comprehensive plots can be made of multiple angles between the syringe and the camera's line of view vs their respective error. This syringe to camera error is defined about the Y axis and can be visualized in **Figure 45:**

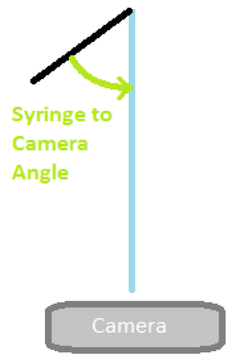

Figure 45: Syringe to Camera Angle Top View Schematic

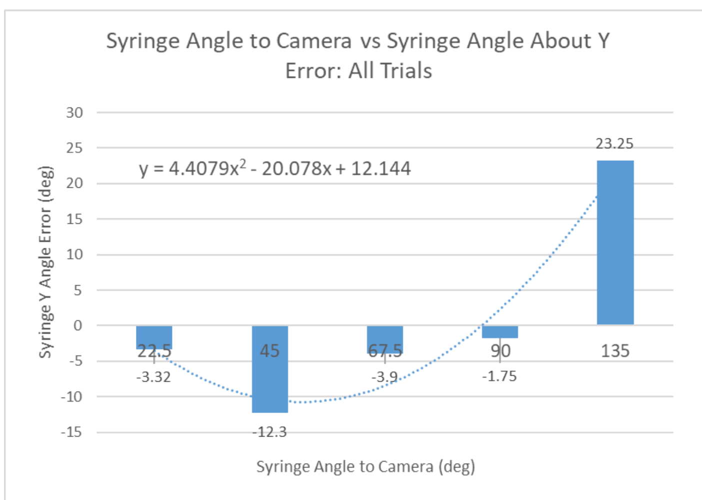

Figure 46

The Y angle error exceeds the tolerance at a syringe to camera angle of 45 and 135, but is within the tolerance for the rest.

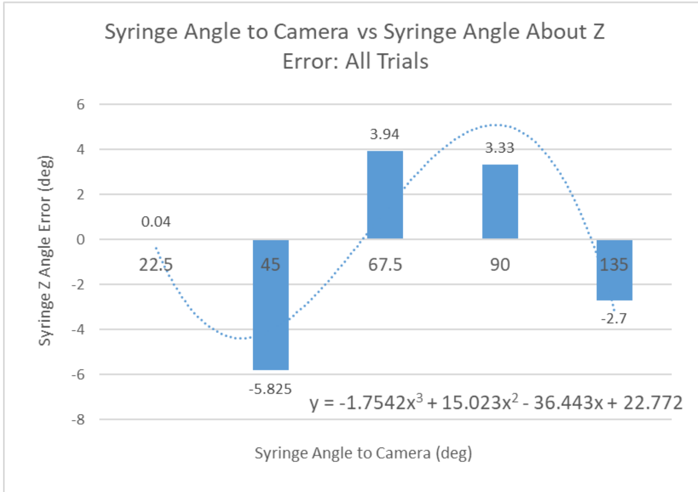

Figure 47

The minimum normal angle is within the tolerance for all syringe to camera angles except for 45 degrees, which barely exceeds the 5 degree threshold. The actual vs experimental syringe to camera angles about the Y axis can also be plotted against each other to use as a form of look up chart (**Figure 48**).

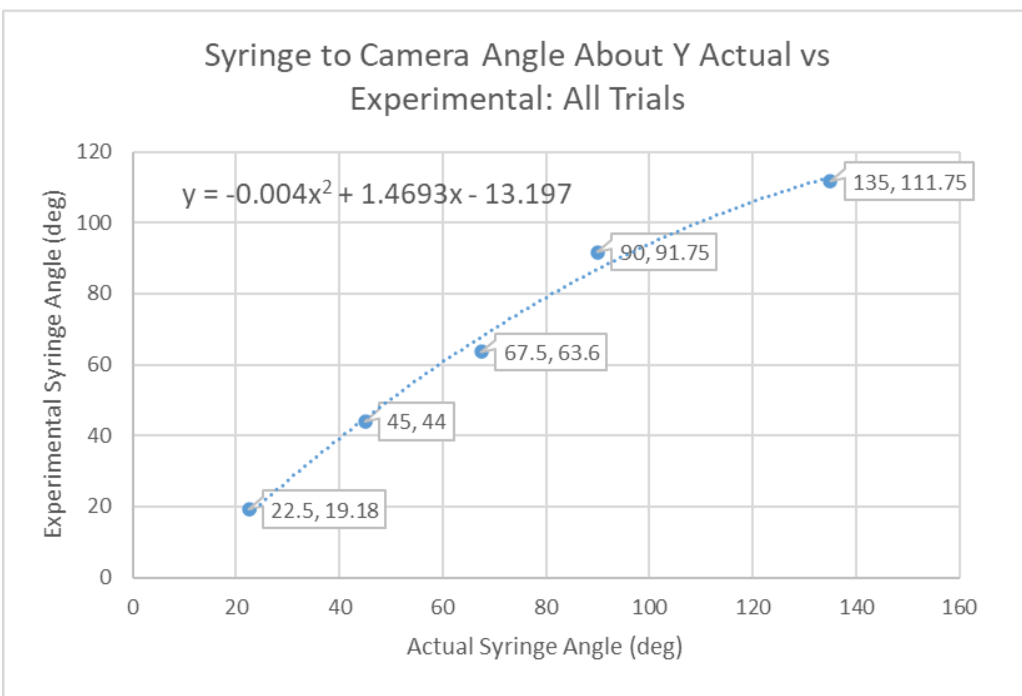

Figure 48

Figure 46-48 and their polynomial line of fit equations can be used to scale/filter the data captured by the depth camera system depending on what angle it detects. It has been shown that some orientations of the syringe and/or shoulder can result in more accurate tracking.

Future Work

This system can continue to be developed to be more accurate, reliable, and user friendly. For starters, further accuracy testing is warranted to program an appropriate filter for angle measurement data collection. Additionally the system can be made more robust by improving depth measurement accuracy of the color markers. During some tests, the RealSense camera would not recognize the color markers or the syringe in the depth frame (refer to **Figure 49**) because they are such small objects.

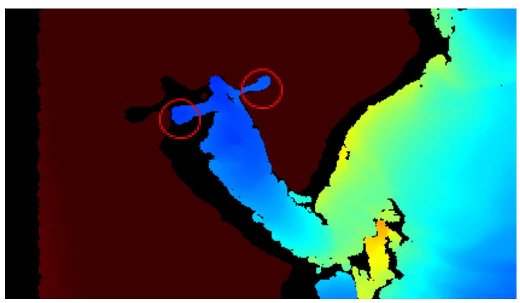

Figure 49: Depth Frame Image: Holding the Syringe

The syringe is seen visibly in **Figure 49**, but this can change depending on light, Intel RealSense setting, and position. One method employed to improve depth accuracy of the color markers was to scan over the 400 or so pixels surrounding the pixel identified as being in the center of the color marker, and passing each one through an if else statement, scoring the pixels with a depth within a specified range, and averaging them. In another group of thought, different methods could be explored to identify the syringe and its location/orientation in 3D space. One could explore training an OpenCV object detection model with syringe data to possibly yield better results. Finally, there is much work to be done to make the system real time. As it is 2 separate scripts capture the shoulder plane and syringe position one after another, then raw position data is written to a spreadsheet where it is processed to find metrics such as velocity and angle. Measuring the shoulder and syringe simultaneously as well as automating some of the data processing would greatly improve the system.

The ultimate goal of this system is to be used in an organized study, which could be two fold. One study could collect kinematic data of nursing students practicing injections, providing them with feedback, and tracking their improvement in technique. The second study could be more centered around general data collection, and involve nurses with varying experience, to update the field on the state of injection technique.

Conclusion

Two systems were developed with the intention to collect kinematic data of an intramuscular injection, more specifically injection velocity, angle, and rate. These three 3 KPIs are under researched and collected data could prove to be a useful tool to nurses and the medical field in general. The successful system used an Intel RealSense Depth camera to identify the position of colored markers with time and the contour of a shoulder. The system could track the markers with 98+% consistency and submillimeter accuracy in favorable conditions. The system proved that all 3 KPIs could be measured using a non intrusive and inexpensive system. There is work to be done on calibrating its accuracy, especially when measuring angles, and work to be done to make it a real time system with automated feedback. The end goal is to have the ability to give a nurse feedback on the 3 KPIs moments after they perform the procedure.

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