Assessing Technologies for Post Discharge Follow-up of Orthopedic Surgery

Noshad Rahimi, Matt Nickeson, Parisa Ghafoori
Dept. of Engineering and Technology Management, Portland State University, Portland, OR - USA

Abstract--**This study examines several developing technological alternatives, including computer vision, lab-on-chip blood monitors, and integrated servomotors to meet the needs of post-surgical patient follow-up. Multiple health care provider experts were surveyed using pairwise comparison in a hierarchical decision making model to determine their preferred criteria for addressing these tasks, revealing a preference for quality and protection at the expense of speed. Cost and ease of use were perceived as smaller factors with no strong differences noted between patient and provider effort. The high tech alternatives did not always outrank the current low tech state of the art, particularly for x-ray analysis, although integrated servomotors and lab-on-chip blood monitoring show promise for future development.**

I. INTRODUCTION

Patient follow-up is a necessary part of many medical procedures, but may be one of the least technologically advanced forms of medicine today. In an age of electronic medical records, digital CT scans, and at-home medical trackers, post-surgery follow-up still requires the old-fashioned method of booking an appointment, traveling to the office in-person, and waiting.

Due to legislation and policies on handling medical records, adapting new technologies to various aspects of healthcare in which patients' data and information is being handled has been a major challenge for both healthcare providers and policymakers (see [1]–[5]). In addition to this, the reliability of many adapted technologies have been a point of concern for the past several years, and therefore has been studied extensively (see [6]–[10]).

Orthopedic surgery, as a widely practiced field of modern medicine, is not an exception to these issues. On one hand, there is a need for moving away from the old-fashioned methodologies that are both time and resource intensive (for both the healthcare provider and the patients); and on the other, there needs to be transition in a fashion that is in complete compliance with HIPAA and other policies regarding patients' information, while adapting more convenient and time saving technologies such as electronic prescriptions, replacing conventional office appointments with online or automatic interfaces, and providing more technologically advanced alternatives for lab tests and data collections.

This paper is intended to study the feasibility of such a transition for the post-surgical patient follow-up of orthopedic surgery. A Hierarchical Decision Model (HDM) was developed and utilized to gather expert judgments on the various technologies that are currently available and could potentially replace the conventional methods. The structure of the paper is as follows: Section II describes the Background and Literature Review on the subject; Section III describes the Gap Analysis between the current technologies and potential alternatives; Section IV explains the HDM methodology; Section V covers the Model Implementation; Section VI shows the developed Model; Section VII reports the HDM results and an analysis of the gathered data; Section VIII discusses the Implications of the study; and finally, Section IX shows the Concluding Remarks.

II. BACKGROUND

Orthopedic surgery is an unfortunately large part of modern medicine; with millions of patients around the world in constant need of medical intervention for broken bones, osteoarthritis, bone tumors, and other musculoskeletal injuries [11]. Patients often undergo non-surgical treatment prior to surgery to try and resolve their issues without invasive and costly procedures, although in cases of trauma the surgery is often performed quickly after the injury takes place [12]. Surgical results are quite positive overall, although patients often underestimate the amount of follow-up required even when a surgery is successful.

A. Patient Follow-up

Patient follow-up is a required part of the recovery process after surgery, but is one of the least technologically advanced aspects of modern medicine. Typical follow-up post-discharge involves scheduling appointments and returning to a clinic where a health care provider (HCP, either a doctor, nurse or physical therapist) administers a standard set of diagnostics to assess patient healing and wellbeing. Specific follow-up tasks after orthopedic surgery include:

- Blood tests (to check for infection)
- X-ray imaging (to directly observe bone healing)
- Medicine and Pain Management (to address patient pain or other concerns)
- Physical therapy (to improve motion/strength)
- Subjective and Objective diagnostics [12] (to standardize patient results against pre-established scoring methodologies)

B. Telemedicine

Telemedicine, defined as "the use of telecommunications and information technology to provide health care services to persons at a distance from the provider" [13] is seen as a promising group of technologies which could improve many aspects of medicine, especially care required after a patient is discharged from surgery.

Medical literature has been reviewed to find out about the current state-of-the-art for telemedicine. It seems that although many different areas are being studied, there is no consistent usage for this technology. The highest regular use of technology appears to be the telephone, used in many cases for routine follow-up after care [14]–[16].

Also, remote monitoring technologies have recently been more diffused, specifically in critical care populations such as heart failure monitoring [17] This study was interesting as it looked at the larger picture by performing a cost-utility analysis to justify the use of such technologies and also showed that while the health care providers had to pay more [see Table 1], the patients themselves had to pay less, and when combined with the analysis of "Quality-Adjusted-Life-Years" showed a benefit for the technological solution. Quality-adjusted-life-years look at the remaining years left in a patient's life and assign a value to each year, taking account the earning potential and activity level for each year; younger years are worth more than older years to the overall system although clearly individual patients may disagree.

This also established a theoretical baseline at which the additional costs of technology implementation could be measured [see Table 2]. In this analysis, even adding a fee of 900 Euros for the patient would still produce a net benefit when the overall cost-benefit analysis is complete.

An earlier meta-analysis [13] (c. 2000) was performed in Sweden to analyze this question of cost-effectiveness and produced a very consistent set of criteria by which to judge the technologies:

"<u>The possible costs (and savings) of telemedicine would include:</u>
1. Hardware
2. Software
3. Consultants' time
4. Travel costs
5. Running costs (e.g. telephone line and rental charges)
6. Administrative changes
7. Staff changes
8. Number of referrals
9. Treatment costs

TABLE 1 –HEALTH CARE COSTS BETWEEN STANDARD AND REMOTE TREATMENT [17]

Health care system costs	**Costs (€), mean (SD)**		**Mean difference (95% CI)**	***P* value**
	Standard arm (n=101)	Remote arm (n=99)		
Protocol-defined clinic visits	90.29 (38.58)	56.63 (38.64)	33.66 (22.89, 44.43)	<.001
ED visits and urgent in-office visits	23.60 (33.68)	14.80 (24.71)	8.81 (0.56, 17.06)	.04
Nonurgent in-office visits	20.13 (38.71)	30.81 (72.13)	–10.68 (–26.78, 5.42)	.19
Scheduled remote follow-ups	0.00 (0.00)	32.50 (9.20)	–32.50 (–34.34, –30.67)	<.001
Unscheduled remote follow-ups	0.00 (0.00)	56.42 (58.95)	–56.42 (–68.18, 44.67)	<.001
Hospitalizations	1945.82 (5247.62)	1722.02 (4106.00)	223.80 (–1091.83, 1539.44)	.74
Diagnostic examinations	50.16 (73.23)	49.60 (77.80)	0.56 (–20.50, 21.63)	.96
Mean annual cost per patient	2130.01 (5251.33)	1962.78 (4185.61)	167.23 (–1158.61, 1493.06)	.80

TABLE 2 - COST UTILITY FOR REMOTE TECHNOLOGY [17]

Cost-utility variables	**Value, mean (SD)**		**Mean difference (95% CI)**	***P* value**
	Standard arm (n=91)	Remote arm (n=89)		
Mean utility value at baseline	0.737 (0.234)	0.793 (0.179)	–0.055 (–0.117, 0.006)	.08
Mean utility value at 16 months	0.711 (0.305)	0.754 (0.275)	–0.043 (–0.128, 0.043)	.32
QALYs (controlling for baseline)	0.966 (0.231)	1.032 (0.177)	–0.066 (–0.126, –0.005)	.03
Mean cost per patient (€)	2962.80 (7323.93)	2074.70 (4581.30)	–888.10 (–906.75, 2682.95)	.3

The consequences (positive or negative) may be directly related to health or not. The health benefits would include:

1. Effect of bringing treatment forward in time (e.g. changes in patient management)
2. Clinical confirmation (e.g. second opinions)

Non-health benefits would include:

1. Improved quality of service
2. Transfer of skills
3. Speed of service
4. Education"

Granted, in 2000 some of the technologies were focused on simple video-conferencing as this pre-dates the rise of the modern Internet, software apps, and smartphones, but the criteria involved remain the same. A cost-consequence matrix [see Table 3] was also introduced to judge the impact of a given technology, which takes into account the very real monetary costs of a new technology [18]. If the positive impact does not outweigh the costs the technology may not be worth using in that instance.

TABLE 3 - COST/CONSEQUENCE TABLE [18]

	Consequences			
Costs	**Beneficial**	**Little Difference**	**Negative**	**Insufficient Evidence**
Cost Savings	+	+	+/-	?
Little Difference	+	+/-	-	?
Greater Costs	+/-	-	-	?
Insufficient Evidence	?	?	?	?

III. GAP ANALYSIS

Prior to selecting the best alternative for the current technologies, there is a need to identify the current state of the situation and define what needs to be done to meet the objectives of the research. Gap analysis is a useful tool for comparing between the current and future status, along with the tasks that need to be done to accomplished to transition between the two [19]. A useful metric to understand the current and future status of the technology and industry has been proposed by Linstone and is called the TOP methodology [20].

TABLE 4 - GAP ANALYSIS RESULTS

Gap Analysis	**Requirements**	**Capabilities**	**Gap**
Organizational	• Low Cost • Regulations • Information Security • Interoperability • Customer Satisfaction • Consistency • Maintenance • Adaptable • Analyzable	**Low Tech** • Labor intensive • Inconsistent • Slow to change • Limited Availability **High Tech** • Secure • Consistent • Comprehensive • Data Analysis	There is a need for a more adaptable and consistent alternative that allows data analysis and meets regulations. Cost may be flexible if capability is improved
Personal	• Easy to Use • Fast • Efficient • Accurate • Privacy • Low Cost • Convenient • Human Relationship	**Low Tech** • Privacy • Slow • Low convenience • Trusted/ established **High Tech** • Fast • Convenient • Secure	There is a need for a more convenient and trustworthy alternative that maintains privacy without adding major cost or high training.
Technical	• Long Service Life • Reliability • Secure • Form Factor • Ease of Use • Access • Fast • Labor • Efficient Jobs to be done ✓ Blood Test ✓ X-Ray ✓ Medicine & Pain Management ✓ Physical therapy (Mobility) ✓ Post-surgical Orthopedic subjective score ✓ Post-surgical Orthopedic objective score	**Low Tech** • Low reliability • Uneven Effectiveness • Inconsistent • Human Contact **High Tech** • Fast • Comprehensive Data • Repeatable • Convenient self-survey scoring • Automated alerting	There is a need for effective, cheap, and easy to use technology to perform following tasks: • Automatic blood testing • X-Ray at home • Physical interaction for measurement or therapy

The TOP simply breaks down the overall system and looks at it from three different perspectives:

- Organizational: Which looks at the organization as a unit that is battling competitors, and with internal challenges;
- Personal: Sees the organization from the perspective of the individual for job security, a step to gain prestige or simply any other personal gain or loss associated with the organization;
- Technical: This perspective sees the organization as hierarchical structure, and then it models by utilizing system dynamics and also discusses objective, rational criteria.

A TOP methodology was adopted to compare between the different perspectives present in this situation. Capabilities were also divided between low tech (similar to current usage today) and high tech (or developing) solutions.

IV. HDM BACKGROUND/METHODOLOGY

In this project, a hierarchical decision model tool (HDM) is used for evaluating patient follow-up telemedicine technologies. HDM tool is a comprehensive and logical framework, which produces multi-level decisions under multiple criteria. Many authors have been using HDM modeling in order to compare between multiple technological options [21]–[24].

A hierarchical decision model consists of three main tiers: a goal, criteria, and alternatives [25]. Criteria of the same level are compared in a one-to-one, pairwise comparison, process with respect to the overall goal. The alternatives are evaluated for how preferred they are with respect to each criterion at the very last level, the farthest from the goal level [26].

The HDM tool provides a better understanding of complex decisions and allows the problem to be structured into a hierarchal tree. As mentioned above, the goal, criteria and alternatives are the three major levels in most decision problem's hierarchy. The objective of the decision is represented at the top level of the hierarchal tree. Next the criteria and all possible sub-criteria are represented in the middle levels. Lastly, the decision alternatives are placed at the lowest level of the hierarchal tree. Figure 1 below is a general representation of the Hierarchical Decision Modeling tool (HDM).

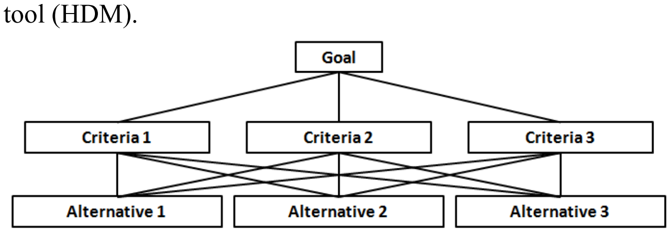

Figure 1 - HDM Format

In the following sections, the work main objective will be restated; the criteria and sub criteria will be laid down and detailed with respect to their contribution and importance to the patient follow-up process.

V. MODEL IMPLEMENTATION

According to the literature review and consultation with orthopedic surgeons and other professional care givers, there is currently no specific tool or systematic methodology available to conduct a post-surgical patient follow-up. Patients visit the doctors' office within three weeks, 6 months and/or 1 year after the surgery on average, to perform a post-surgery follow up. They have to book appointments over the phone and visit the doctor's office and a medical lab to perform all the required tests and evaluations. None of these include a technology that would systematically replace any of the conventional methods. Therefore, a model was created to evaluate current available technologies that can replace the old-fashioned methods in a faster and more reliable way, and propose an alternative solution based on the results of the HDM model.

In order to create the HDM model, a set of criteria and sub-criteria needs to be defined based on literature review. Once these criteria and sub-criteria were selected, they were consulted with experts to verify the comprehension of the model and applicability of the selected criteria. The result of this practice is the HDM model that was implemented for this study, and it is shown in Figure 2 below:

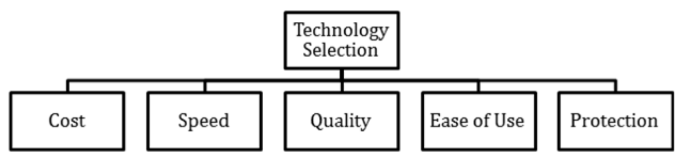

Figure 2 - HDM Categories

A. Category Details

In this section the categories and sub-categories will be spelled out and detailed, based on the elementary discussions with the experts, and literature review.

1) Cost:

- Patient Cost
- Provider Cost

Cost is an obvious measure of almost any technology, especially when comparing between widely disparate methods of accomplishing tasks. Costs are split in this analysis between direct costs to patients (or their insurance) and provider-side costs (such as capital equipment or administrative costs).

2) Speed:

- Preparation / Travel Time
- Test Duration
- Response Time

Speed is another obvious measure of technology, although it is sometimes overlooked in non-emergency medicine. However, it is well-known that consumer behavior can be heavily influenced by the duration of a transaction. Speed is broken down into the time a given task takes to arrange, complete, and when the results are made available.

3) Quality:
- Data Integrity
- Reliability

Quality in this case refers to the results of the data itself and is separated into integrity of the data (its transferability, accessibility, and storage life) and the reliability, accuracy, and trustworthiness of the data measurement.

4) Ease of Use:
- Patient Learning Curve
- Provider Learning Curve

Ease of use is a clear driver of consumer behavior, and patients and HCP are not immune to this. Especially when trying to break people out of existing habits or long-held training regimens, the learning curve and training time is critical.

5) Protection:
- Public Safety
- Data Security

In the digital age, people are increasingly paranoid about data security, doubly so when it is personal medical data. Federal laws strongly protect patients' medical data (HIPAA and other laws) and compatibility with these laws represents data security, while public safety refers to the physical safety measure of the alternative technology being used.

B. Technology Alternatives

In Table 5 below, alternatives have been ordered from high tech, representing newer and emerging technology capabilities that may or may not be fully implemented for medical use, to low tech, representing the existing state of medicine. Through research and expert interview, this section includes the scoring of alternatives in each of the six job categories in relation to the sub-criteria identified in the HDM model. These solutions do not have to be bundled within each column as each job may have a different best solution; for instance, home blood monitors may have great benefits while x-rays are still best left to health care facilities.

1) Blood Test

Testing blood to monitor the appropriate recovery of the patients includes monitoring any possibility of developing infection. There are four alternatives identified for this task as described below: The traditional method of in-person lab tests, conducting the test by a technician at patient's location, self-treatment (or by a caregiver) blood monitoring machines, and new lab on chip devices.
- Blood Monitor – These are advanced home blood monitoring machines that facilitate regular measurement and can potentially store blood readings for regular reporting. In our study we assumed that while most of these monitors are designed to be intuitive to users, home patient use is not necessarily as reliable as the test conducted by health care professional [27].
- Lab-on-chip – or LOC is often a small device that contains a very small chip which incorporates one or more laboratory functions in it. It often requires a very small amount of fluid to conduct its test [28].
- House call – similar to the in-person lab test but conducted at patient's residence.
- In-person lab test – the current standard, using professionally trained lab personnel at a dedicated laboratory after drawing blood and sending in for analysis.

TABLE 5 - TECHNOLOGY ALTERNATIVES

	High Tech	→	→	**Low Tech**
Tasks	*Alternative 1*	*Alternative 2*	*Alternative 3*	*Alternative 4 (Traditional)*
Blood Test	Blood Monitor [27]	Lab-on-chip [28]	House call	In-person lab test
X-Ray	Portable X-Ray device [29]	N/A	House call [30]	In-person lab X-Ray
Medicine & Pain Management	Pain pump [31]	Website / Software app [32]	N/A	Consultation at facility
Physical Therapy	Integrated servo [33]	Nerve stimulator [34]	House call	Consultation at facility
Subjective Orthopedic Score	Website / Software app [12], [35]	Phone call	N/A	Consultation at facility
Objective Orthopedic Score	Integrated servo [33]	Computer vision [36], [37]	N/A	Consultation at facility

Ranking alternatives:

Cost: Studies show the new innovative lab-on-chip devices are very cost effective[38]. These savings are shared by both the patients and the providers[39]. Hence, lab-on-chip alternative comes best in cost category and obtain a score of “1” while the rest of methods receive a “0” score.

Speed: Aside from the test duration where all the alternatives take relatively the same amount of time, when it comes to the preparation and response time the lab-on-chip is the winner due to its availability and ease of use [40].

Quality: In terms of quality, both in data integrity and reliability, studies suggest lab-on-chip are as accurate as traditional in-lab tests with the difference that lab-on-chip can provide better data integrity as it can potentially send the test result directly to the doctor automatically. Hence the lab-on-chip gets “1” in both sub-criteria while in person lab test also gets “1” for reliability [41].

Ease of Use & Protection: In both categories lab-on-chip obtains the high score across the board[42], except the patient learning curve as even though often the test only requires a drop of blood, it still needs the patient to get involved which could introduce potential risk [43].

2) X-ray

The second category of jobs to be done is the need for X-ray tests to monitor the proper healing of the bones and joints. The three alternatives for this task are described below: the traditional method of in-person lab test, conducting the test by a technician at the patient’s location using a portable X-ray unit, and self-treatment (or by a caregiver) X-ray scanning machines.

- Portable X-Ray Device – This device is a commercialized unit that can be utilized by the patient themselves (or their caretakers) to scan and send the X-ray information to the healthcare provider. The device would have a manual or user guide and would require the patient to understand the functionality and correct use prior to implementation [29]
- House call – Similar to the in-person lab test but conducted at a patient’s residence. The healthcare professional could utilize a more robust yet still portable X-Ray machine [30].
- In-person lab X-ray – the current standard, using professionally trained lab personnel at dedicated laboratory performing X-ray scanning and sending in for analysis.

Ranking alternatives:

Cost: Looking at the prices for some samples of the portable and the more robust devices for the X-ray machines, and considering the number of X-ray devices required for the healthcare provider to attain and maintain, and also the costs for the patients to utilize such devices, the in-person lab test seems to be the most affordable [30], [44].

Speed: When it comes to preparation time the portable device is the quickest, since it does not need any travel time for the test. The testing duration seems to be the quickest for the in-person test as the device is already set up and ready to use, and also there is minimum application error due to patient or caregiver’s lack of knowledge in the case of the Portable X-ray. Since the film development facility is already within the lab, the in person test has the quickest response time [29], [44]

Quality, Ease of Use & Protection: In case of quality, since the patient or caregiver user is inexperienced in case of the portable x-ray device, and thedevices that are used for the house visits may be less robust than of those in the lab, the integrity of the data and accuracy of the test are the best in the in-person lab test, as well as the ease of use and safety issues [30], [44], [45].

Criteria	Cost		Speed			Quality		Ease of Use		Protection	
Subcriteria	Cost to Patient	Cost to Provider	Preparation (Travel) Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security
Blood monitors	0	0	0	1	0	0	0	0	1	0	0
lab on chip	1	1	1	1	1	1	1	0	1	1	1
House call	0	0	0	1	0	0	0	1	0	1	0
In person lab test	0	0	0	1	0	0	1	1	0	0	0

Figure 3 - Blood Test Alternative Scores

Criteria	Cost		Speed			Quality		Ease of Use		Protection	
Subcriteria	Cost to Patient	Cost to Provider	Preparation (Travel) Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security
Portable X-Ray Device			1								
House Visit											
In-person lab X-Ray	1	1		1	1	1	1	1	1	1	1

Figure 4 - X-ray Alternative Scores

3) Pain Management

There is a need for pain and medicine management to monitor the proper intake of the medication and ensure that the patient is not having excessive pain. The three alternatives for this task are described below: the traditional method of in person consultation, interacting with the healthcare provider through a software application or online website to provide data and get medication prescribed, or utilizing an automatic monitoring pain pump.

- Pain Pump – A pain pump would deliver the pain medication directly to the patient's blood circulatory system. The device would be capable of registering and logging patient's medication intake and would provide that to the healthcare provider to manage the medication process. A similar, less integrated pain pump is currently developed and commercialized by Medtronic [31].
- Website / Software App – This is an online application or website that would allow the patient to enter and record the medication and pain information and also receive proper refills or medications through electronic prescription. Healthcare providers have access to online clinical information as well [32].
- Consultation at facility – the current standard, using professionally trained medical personnel that consult with the patients on their pain levels and prescribe recommended medication and intake dosage.

Ranking alternatives:

Cost: The proposed pain pump technology here is a more advanced version of the current pain pumps in the market. Even assuming the added monitoring feature to the pump to have no impact on cost, the utilization of e-prescription is the most affordable of all three alternatives [46].

Speed: When it comes to preparation time, the software app/website alternative would get the highest ranking. The reason for this is that they don't require setup (contrary to the pain pump) nor does it need travel time (contrary to the in-person consultation). However, the quickest test duration would go to the pain pump, where it does not need any forms to fill or prescriptions to review. Since the pain medication is readily available with the case of the pain pump, and the device monitors the medication intake automatically, it has the quickest response time compared to the in person consultation and website, for which the medication will be available after the test [31], [46].

Quality: The features of software applications & websites make them the most uniform and comprehensive databases among the other alternatives that can be quickly accessed online[46]. The in-person interaction gathered by the healthcare provider (instead of patients' own judgment) would make the in-person consultation the most reliable.

Ease of Use: Since the in-person consultation allows the patient to have immediate assistance without any ambiguity and/or questions by the experienced healthcare provider, and it does not require working with a new device or software, it has the highest rank in the learning curves.

Protection: The real-time observation of the healthcare provider allows the patient to have the proper amount of medication at various intervals, rather than relying on their perception of the correct amount of medication needed.

4) Physical Therapy

Physical therapy can be required for a long duration after surgery, and early usage can improve patient outcomes. Since the computer vision devices and innovative integrated servo technologies are neither mass produced nor yet commercialized, the study scores the alternatives based on the research and literature review comparing them with more traditional physical therapy methods. Below are the research and the scoring of these post orthopedic surgery follow up treatments:

- Integrated Servo – this is a developing technology which would physically install a servomotor mechanism onto the patient's affected limb(s). This servo could then register range of motion and strength calculations automatically without additional steps by the patient or provider [47]. One example of an upcoming application of this is the Titan Arm [33].
- Computer Vision – this developing technology utilizes infrared camera tracking technology and software processing to observe human motion and translate this into usable data. Currently used mainly for home entertainment [36], [37], this non-contact technology has become much more inexpensive and reliable for medical use and can be easily adapted to observe valid medical metrics, including pulse rate, in real-time [48].
- House call – similar to traditional therapy methods, but takes place at patient's residence.
- Consultation at facility – the current standard, using specially trained personnel at dedicated facility

Ranking alternatives:

Cost: Research promises great cost saving through usage of integrated servo as well as computer vision devices. A study by Mitchell and deLissovoy of Georgetown University and Johns Hopkins University realizes an approximate saving

Criteria	Cost		Speed			Quality		Ease of Use		Protection	
Subcriteria	Cost to Patient	Cost to Provider	Preparation (Travel) Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security
Pain-pump				1	1						
Software App	1	1	1			1					1
In-person exam							1	1	1	1	1

Figure 5 - Pain Management Alternative Scores

of $1,200 per patient episode of care by deregulation referral from a physician for a physical therapy evaluation and treatment (in the states that the regulation is removed from statutes) [49]. We are assuming that as integrated servos can be readily usable, it potentially provides the same savings in addition to the clinical operational cost savings. While computer vision is associated with lowest cost to the patients, the integrated servo gets the best score on cost to the provider as it is promised to be relatively inexpensive [33] and the assumption is that the clinic could provide these with minimal required operation supervision.

Speed: As the assumption is that every alternative except house calls require some type of preparation or travel time, the house call scores 1 in preparation time. The test duration is scored the same across all alternatives as the treatment itself is assumed to be relatively similar. However, integrated servos as well as computer vision both have the capability of sending the data collected from the treatment via secure network to the physicians, so get the high score in response time.

Quality: In terms of reliability, studies suggest that both integrated servo and computer vision device reliability are in par with that of an in-person session [47].

Ease of Use: When it comes to the provider learning curve, the assumption is that the easiest method is the current traditional method of in-person sessions as it is well established and no change to the practice is required. In the category of patient learning curve, the house call gets the high score, as the assumption is that most of the operation is being controlled and instructed by the therapist.

Protection: In regards to the public safety, since the other technologies are still to prove their promise, the high score is given to the two traditional alternatives but when it comes to data security, the new technologies are designed to securely send information back to the physicians and obtain the high score.

5) Subjective Orthopedic Scores

The next category of jobs to be done is the need for Subjective Orthopedic Scores. These scores measure a patient's perception of their own progress in healing and recovery. The three alternatives for this task are the traditional method of in-person consultation, interacting with the healthcare provider over the phone, or utilizing a website or software application to answer questions yourself.

- Website / Software App – websites [12], [35] are already used to calculate and record these scores in a consistent manner. Dedicated software applications could also be developed to produce a more mobile platform, as well as integrate the measurements into patients' daily lives by automatically asking for feedback throughout the day.
- Phone call – rather than patients traveling to facilities, phone calls can be used to query patients remotely
- Consultation at facility – current standard, taking place at health care facility

Ranking alternatives:

Cost: Similar to the pain and medicine management job, utilizing websites can be very cost efficient for healthcare providers [46], but a phone call can be the most convenient and cost-effective method for the patients, since it won't need an internet connection or travel costs to the office.

Speed: When it comes to preparation time, the software app/website alternative gets the highest ranking. The reason for this is that they don't require an appointment set up (contrary to the other two alternatives) nor require travel time (contrary to the in-person consultation). However, the longest test duration would go to the website, as it lacks the experienced healthcare provider to resolve any ambiguous questions. Since the data is already logged in to the system, the fastest response time for the data to be available would go to the website [12], [35].

Quality: Due to in-person interaction and real-time observation of the healthcare provider of the patient, the higher and more accurate quality data collection belong to the in-person consultation [12], [35].

Ease of Use: Since the in-person consultation allows the patient to have immediate assistance without any ambiguity and/or questions by the experienced healthcare provider, and it does not require working with a new device or software, it has the highest rank in the learning curves [12], [35].

Protection: Once again, since the software collects the data and can utilize verification and security features to ensure data security, and also logs the data right away, it gets the highest rank. There haven't been any discrepancies recorded between the alternatives with regards to public safety [12], [35].

Criteria	Cost		Speed			Quality		Ease of Use		Protection	
Subcriteria	Cost to Patient	Cost to Provider	Preparation (Travel) Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security
Integrated Servo		1		1	1	1	1				1
Nerve Stimulator	1			1	1	1	1				1
House call			1	1				1		1	
In-person session				1			1		1	1	

Figure 6 - Physical Therapy Alternative Scores

Criteria	Cost		Speed			Quality		Ease of Use		Protection	
Subcriteria	Cost to Patient	Cost to Provider	Preparation (Travel) Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security
Software app		1	1		1					1	1
Phone call	1			1						1	
In-person exam						1	1	1	1	1	

Figure 7 - Subjective Test Alternative Scores

6) Objective Orthopedic Scores

The last category of jobs to be done is the need for objective orthopedic scores. These scores measure the mechanical range of motion and functional limits patients can achieve with their limbs. The three alternatives for this task are: the traditional method of in-person tests, interacting with a computer vision device such as the new Xbox One Kinect, or utilizing the aforementioned integrated servo to collect the information directly.

- Integrated Servo – see Physical Therapy above
- Computer Vision – as described earlier, this developing technology uses infrared camera tracking technology and software processing to observe human motion and translate this into usable data. Currently used for home entertainment [36], [37], this technology has become much cheaper in recent years and can be readily adapted to observe valid medical metrics, including pulse rate in real-time [47].
- Consultation at facility – current standard, taking place at health care facility by trained personnel

Ranking alternatives:

Cost: Similar to the pain and medicine management job, utilizing websites can be very cost-effective for healthcare providers [46], especially compared to the price of the computer vision device or travel/staffing expenses for both the patients and the healthcare provider.

Speed: Preparation time would be the quickest for the computer vision as it does not require any travel time (contrary to the in-person visit) nor installation of the device as does the servo. Since the testing duration seems to be similar for all three methods, the same ranking was assigned to them. However, since the captured data is already recorded and does not need any data entry after the test, the in-person test gets the lowest rank [33], [36], [37], [47].

Quality: The integrity of the data is the highest for the integrated servo due to its uniform data collection and capturing method [47]. However, due to lack of trained supervision, the computer vision gets the lowest rank for reliability.

Ease of Use: When it comes to ease of use, the in person exam is the most convenient for the patient, since they don't need to learn any methods of interaction with a device. The healthcare provider is the most convenient with the in-person exam, as they would need training to work with the high tech devices.

Protection: If the patient is working with an experienced HCP, the chances of any physical safety issues are minimized in that alternative. However, since there is no human interaction involved in the data capture or recording, the in-person test would have the lowest data security rank [36], [37], [47], [48].

The Extreme Scale Ranking methodology was utilized to grade each alternative in relation to the criterion and other alternatives. In this approach the best performing alternative(s) obtain score of 1 and others receive 0. In cases where the sub-criterion was not applicable to the task at hand, the uniform grade of 1 was assigned to all alternatives.

Within each criteria, the best choices were given a value of "1" (lowest cost, quickest time, most secure, etc.) while the other (worse) choices were given a value of "0" (higher cost, slower time, less secure, etc.). Rather than use an external utility metric, alternatives were simply ranked relative to each other, using the current state of the art as a baseline comparison. Assumptions were made that developing technologies had been properly implemented for each task and current state-of-the-art standards were used for data transfer and security.

VI. HDM MODEL

Using the criteria discussed above, the HDM model was constructed as shown in figure 9.

Criteria	Cost		Speed			Quality		Ease of Use		Protection	
Subcriteria	Cost to Patient	Cost to Provider	Preparation (Travel) Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security
Integrated Servo		1		1	1	1	1				1
Computer Vision	1		1	1	1						1
In-person exam				1			1	1	1	1	

Figure 8 - Objective Test Alternative Scores

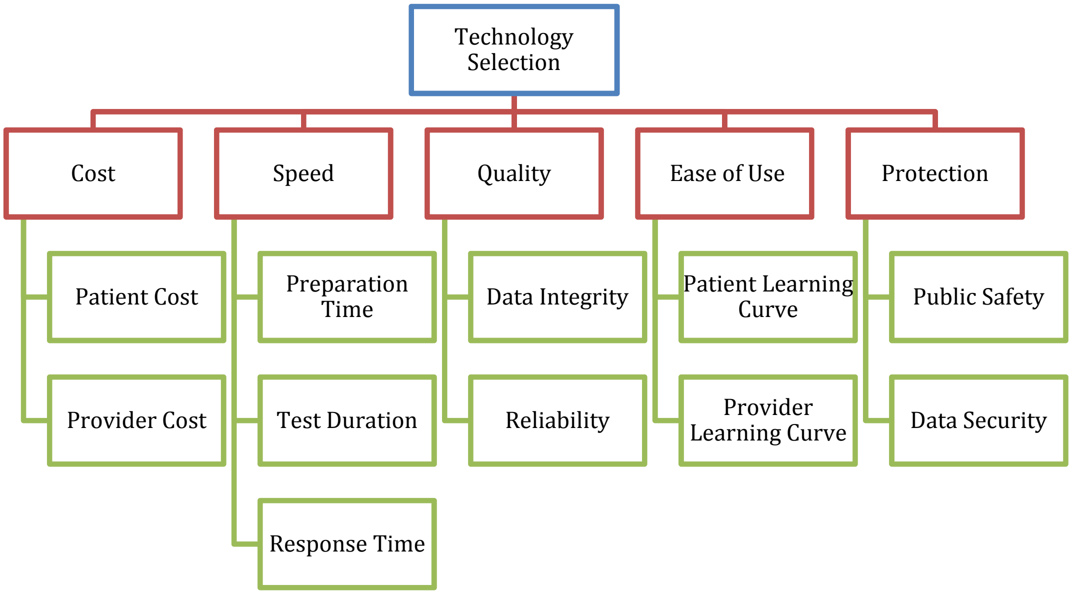

Figure 9 - Overall HDM Model

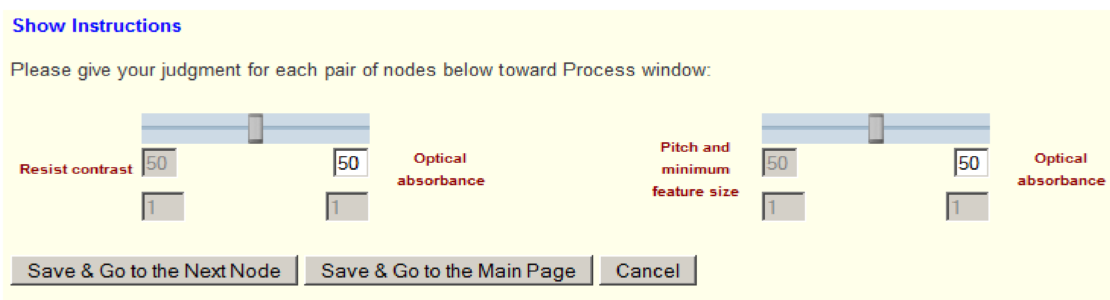

Figure 10 - Pairwise Comparison Example

Cost		Speed			Quality		Ease of Use		Protection	
Cost to Patient	Cost to Provider	Preparation Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security
0.08	0.09	0.02	0.03	0.04	0.13	0.21	0.08	0.08	0.14	0.11

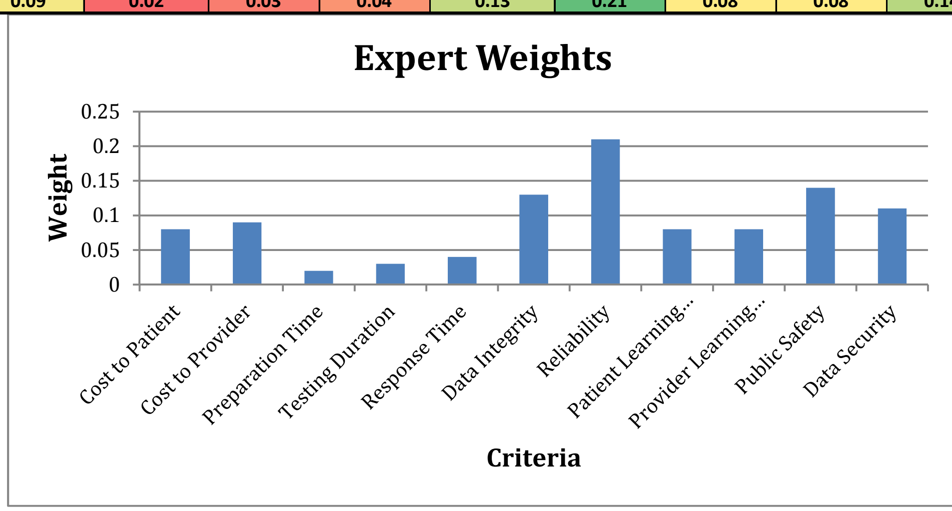

Figure 11 - Expert Weights

In order to facilitate the HDM process, an online version of the model was used [50]. This allowed for the construction of a relatively complex comparison structure through the use of an Excel template, as presented in Appendix A. The expert users were guided through a pairwise comparison process using simple visual sliders to compare between criteria. An example of this interface is shown in figure 10.

The user merely needs to click on a given node to be guided through the entire pairwise comparison process.

VII. RESULTS/ANALYSIS

A. Criteria Weights

The results of the pairwise expert comparison (See Appendix B) are shown in figure 11. Six experts provided feedback, including two licensed and practicing orthopedic surgeons in the US and UK, two medical students, a US medical practitioner, and a nurse practitioner and educator.

As shown in figure 11, there was a clear preference for the "Quality" metrics, with "Speed" metrics being valued the least. Cost and Ease of Use were approximately tied, with Protection being higher ranked than both. As observed in Appendix XI, inconsistency scores were quite low, indicating good agreement between experts.

B. Final Scores

By multiplying the expert weights against the alternative scores a final score for each alternative can be calculated (See Appendix A). The figures show the results for each job.

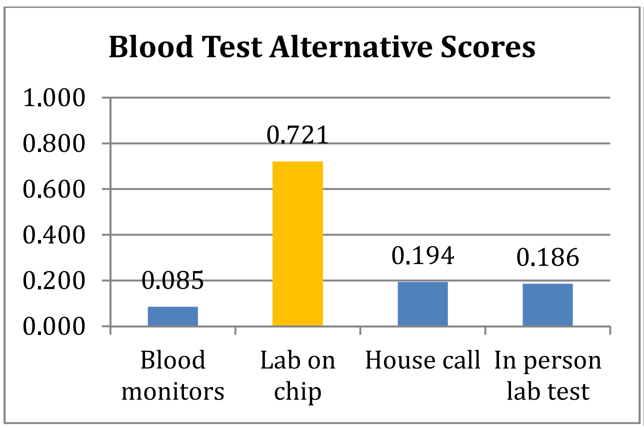

Figure 12 - Blood Test Alternative Scores

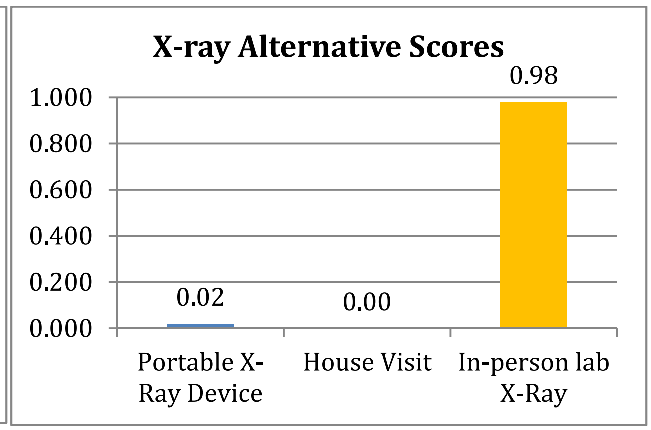

Figure 13 - X-ray Alternative Scores

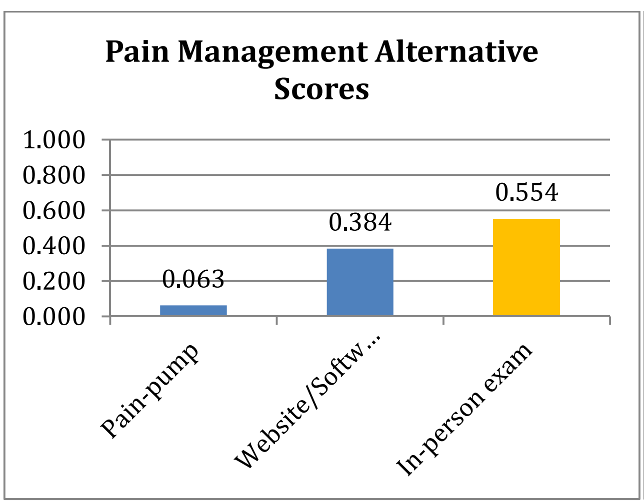

Figure 14 - Pain Management Alternative Scores

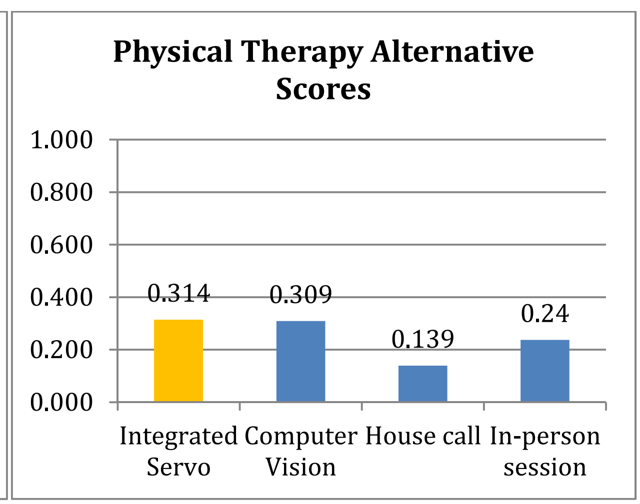

Figure 15 - Physical Therapy Alternative Scores

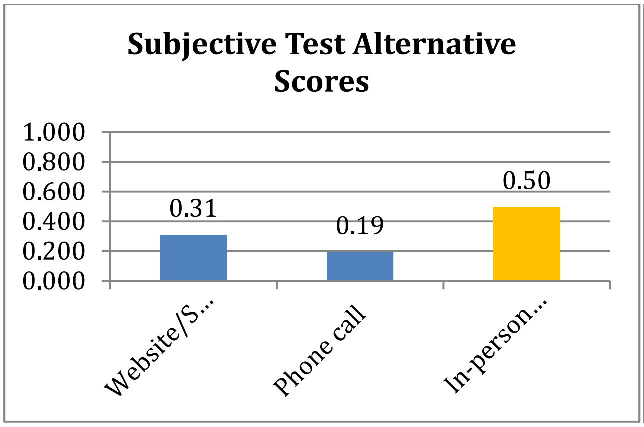

Figure 16 - Subjective Test Alternative Scores

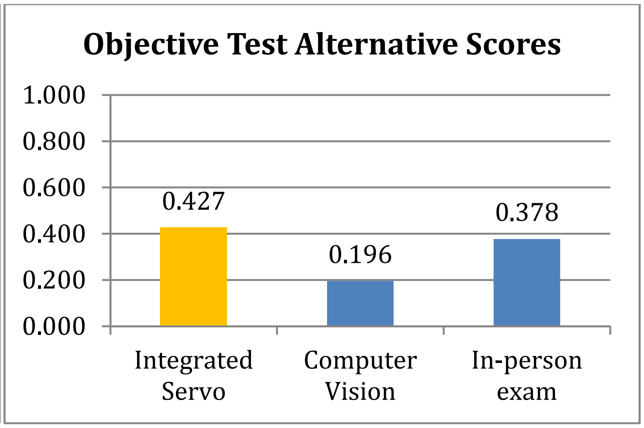

Figure 17 - Objective Test Alternative Scores

According to the results, the following solutions seem to be the most effective for the jobs to be done:

TABLE 6 - TECHNOLOGY SOLUTIONS

Jobs to be done	Proposed Solution	Current Solution
Blood Test	Lab-on-Chip	In-Person Test
X-Ray	In-Person lab X-ray	In-Person lab X-ray
Medicine & Pain Management	In-Person Exam	In-Person Exam
Physical therapy	Integrated Servo	In-Person Session
Orthopedic subjective score	In-Person Exam	In-Person Exam
Orthopedic objective score	Integrated Servo	In-Person Exam

VIII. IMPLICATIONS / DISCUSSION

Expert weights showed that their main interest and point of importance and consideration were as follows:

1. Quality
2. Protection
3. Cost
4. Ease of Use
5. Speed

Looking at these weights and the solutions presented in Table 6, it is reasonable to see how some high tech alternatives could be ranked low compared to the current low tech alternatives. The high tech scores are often low across the criteria except for speed, usually owing to a lack of proven data to demonstrate safety and reliability. However, several of the high tech solutions can be good alternatives to current practice if the costs of utilizing them were justified or subsidized. Specifically, for blood tests, physical therapy, and objective orthopedic scores, the high tech option was found to be potentially valuable compared to the current standards of care.

The lab-on-chip (Figure 8 above) scored almost perfect marks in each criterion, giving it an obvious lead over the other alternatives. Since this type of technology is already commercialized for diabetes monitoring it should not take much effort to implement for infection monitoring after surgery. One potential drawback to this technology is the relatively wide possible range of infection agents which may limit the effectiveness of simpler lab-on-chip technologies.

The integrated servo technology narrowly beat computer vision for physical therapy usage, although one aspect which was outside the scope of this study was the potential for the servo to provide active resistance and feedback during motion which non-contact technology cannot offer. This may not be of much benefit during objective orthopedic scoring, however. Nonetheless, this study shows that this technology should be developed further, potentially by implementing it in conjunction with trained provider care before commercializing home versions.

For x-ray jobs, the safety and quality of the established workflows of the current standards provided a massive advantage. However, with proper training and safeguards in place there could still be a place for personal x-ray usage. Forgoing a hospital visit entirely by diagnosing your own injury could be a significant way to defer health care costs in the future. Proper analysis of the x-ray data will likely still require a trained human element though, as every radiology department will attest to.

For pain management and subjective orthopedic scores, the human element provides quality advantages despite the technological advantages in speed and cost. Even voice contact via telephone cannot overcome the nonverbal communication clues of face-to-face interaction. Future advances in tele-presence technology may provide ways to achieve this connection without a hospital visit.

Overall, it appears that in-person hospital follow-up is still required, although some existing technologies could be readily developed to cut down on the frequency and time spent during these visits. Health care providers should investigate these technologies and think about how to integrate them into their current care regimens to take advantage of modern technology for cost and time savings, indeed even the initial appearance of high-tech solutions may provide a competitive advantage between facilities.

A. Future Work

There have been several limitations to this study:

1. The expert panel that was used was consisted of healthcare providers. It is suggested that in future research, the voice of patients and caregivers are also captured.
2. The ranking methodology that has been used for the alternative scores (Extreme Ranking) does not consider the dimension of scale, scoring alternative success as "all-or-nothing". It is suggested that other methodologies that can rank the alternatives more quantitatively and consider the scale of differences between them are applied.
3. Some of the technologies that are proposed as alternatives are not yet fully developed or commercialized. This imposes a level of ambiguity over the data associated with them, specifically with regards to cost, quality and protection criteria. It is suggested that future studies get conducted to capture more specific data on these alternatives.
4. Alternative effectiveness was not comparatively measured; with each alternative assumed to perform the task equally well (aside from minor data integrity differences).
5. The authors propose to have similar studies conducted to focus on each of the specific jobs individually to get a better grasp of each area of patient follow-up.

IX. CONCLUSIONS

This study examined several developing technological alternatives, including computer vision, lab-on-chip blood monitors, and integrated servomotors to meet the needs of post-surgical patient follow-up. Multiple healthcare provider experts were surveyed to determine their preferred criteria for meeting these tasks. The study revealed the experts consistently ranked quality and reliability followed by protection and safety at the outmost importance factors. This came at the expense of speed, which is usually promised by the technological alternatives. Cost and ease of use were perceived as smaller factors with no strong differences noted between patient and provider effort. As the technological alternatives considered are yet to be mass used and pass the test of time the scores could improve in the future however the current study failed to find strong evidences as to their reliability, protection and safety. As a result the high tech alternatives did not always outrank the current low-tech state of the art, particularly for x-ray analysis, although integrated servomotors and lab-on-chip blood monitoring show promise for future development.

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APPENDIX A – ALTERNATIVE SCORE CALCULATION

	Criteria	Cost		Speed			Quality		Ease of Use		Protection		Total	
	Subcriteria	Cost to Patient	Cost to Provider	Preparation/Travel Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security		
Blood Test	Blood monitors	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.11	0.09
	Lab on chip	0.08	0.09	0.02	0.03	0.04	0.13	0.21	0.00	0.08	0.14	0.11	0.93	0.72
	House call	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.08	0.00	0.14	0.00	0.25	0.19
	In person lab test	0.00	0.00	0.00	0.03	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.24	0.19
X-Ray	Device	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02
	House Visit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00
	In-person lab X-Ray	0.08	0.09	0.00	0.03	0.04	0.13	0.21	0.08	0.08	0.14	0.11	0.99	0.98
Medicine & Pain Management	Pain-pump	0.00	0.00	0.00	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.06
	Website/Software App	0.08	0.09	0.02	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.11	0.43	0.38
	In-person exam	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.08	0.08	0.14	0.11	0.62	0.55
Physical therapy (Mobility)	Integrated Servo	0.00	0.09	0.00	0.03	0.04	0.13	0.21	0.00	0.00	0.00	0.11	0.61	0.31
	Computer Vision	0.08	0.00	0.00	0.03	0.04	0.13	0.21	0.00	0.00	0.00	0.11	0.6	0.31
	House call	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.08	0.00	0.14	0.00	0.27	0.14
	In-person session	0.00	0.00	0.00	0.03	0.00	0.00	0.21	0.00	0.08	0.14	0.00	0.46	0.24
Post surgical orthopedic subjective score	Website/Software App	0.00	0.09	0.02	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.11	0.26	0.30
	Phone call	0.08	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.13
	In-person exam	0.00	0.00	0.00	0.00	0.00	0.13	0.21	0.08	0.08	0.00	0.00	0.5	0.57
Post surgical Orthopedic objective score	Integrated Servo	0.00	0.09	0.00	0.03	0.04	0.13	0.21	0.00	0.00	0.00	0.11	0.61	0.43
	Computer Vision	0.08	0.00	0.02	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.11	0.28	0.20
	In-person exam	0.00	0.00	0.00	0.03	0.00	0.00	0.21	0.08	0.08	0.14	0.00	0.54	0.38

APPENDIX B – INDIVIDUAL EXPERT JUDGMENTS

	Cost to Patient	Cost to Provider	Preparation Time	Testing Duration	Response Time	Data Integrity	Reliability	Patient Learning Curve	Provider Learning Curve	Public Safety	Data Security	Inconsistency
AM	0.08	0.08	0	0.01	0	0.18	0.16	0.12	0.12	0.15	0.1	0.01
CR	0.1	0.06	0.03	0.06	0.05	0.11	0.16	0.13	0.07	0.09	0.14	0
KK	0.04	0.16	0.04	0.02	0.14	0.1	0.1	0.09	0.11	0.04	0.16	0
LN	0.06	0.03	0.01	0.01	0.01	0.14	0.21	0.01	0.01	0.4	0.1	0.03
PM	0.05	0.05	0.01	0.01	0.03	0.13	0.53	0.05	0.05	0.06	0.04	0.01
PZ	0.13	0.13	0.03	0.06	0.03	0.11	0.11	0.06	0.1	0.12	0.12	0
Mean	**0.08**	**0.09**	**0.02**	**0.03**	**0.04**	**0.13**	**0.21**	**0.08**	**0.08**	**0.14**	**0.11**	
Min	**0.04**	**0.03**	**0.01**	**0.01**	**0.01**	**0.1**	**0.1**	**0.01**	**0.01**	**0.04**	**0.04**	
Max	**0.13**	**0.16**	**0.04**	**0.06**	**0.14**	**0.18**	**0.53**	**0.13**	**0.12**	**0.4**	**0.16**	
Std. Dev.	**0.03**	**0.05**	**0.01**	**0.02**	**0.05**	**0.03**	**0.15**	**0.04**	**0.04**	**0.12**	**0.04**	
Disagreement												**0.05**

The statistical F-test for evaluating the null hypothesis is obtained by dividing between-subjects variability with residual variability as below. The F-test value indicated the degree in which the inputs disagree. Here we observe the inputs are from a wide range with high level of disagreement.

Source of Variation	Sum of Square	Deg. of freedom	Mean Square	F-test value
Between Subjects:	0.19	10	0.019	3.27
Between Conditions:	0	5	0	
Residual:	0.28	50	0.006	
Total:	**0.47**	**65**		
Critical F-value with degrees of freedom 10 & 50 at 0.01 level:				**2.7**
Critical F-value with degrees of freedom 10 & 50 at 0.025 level:				**2.32**
Critical F-value with degrees of freedom 10 & 50 at 0.05 level:				**2.03**
Critical F-value with degrees of freedom 10 & 50 at 0.1 level:				**1.73**