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Finding NEEMO: towards organizing smart digital solutions in orthopaedic trauma surgery

Benedikt J. Braun[1]
Bernd Grimm[2]
Andrew M. Hanflik[3]
Meir T. Marmor[4]
Peter H. Richter[1]
Andrew K. Sands[5]
Sureshan Sivananthan[6]

- There are many digital solutions which assist the orthopaedic trauma surgeon. This already broad field is rapidly expanding, making a complete overview of the existing solutions difficult.
- The AO Foundation has established a task force to address the need for an overview of digital solutions in the field of orthopaedic trauma surgery.
- Areas of new technology which will help the surgeon gain a greater understanding of these possible solutions are reviewed.
- We propose a categorization of the current needs in orthopaedic trauma surgery matched with available or potential digital solutions, and provide a narrative overview of this broad topic, including the needs, solutions and basic rules to ensure adequate use in orthopaedic trauma surgery. We seek to make this field more accessible, allowing for technological solutions to be clearly matched to trauma surgeons' needs.

Keywords: digital; orthopaedic surgery; technology assessment

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Introduction

We live in an age where new technologies are constantly being developed to tackle a wide variety of problems, changing the way we live, communicate, travel and work. Today, new technologies are mainly digital solutions which use computing power, data, telecommunication, sensors and interfaces in stationary, mobile, connected or networked applications to generate, analyse and visualize information and make it actionable. Medicine is subject to rapid development and change. Many, if not all, of the digital technologies being developed, are applicable to orthopaedic trauma. Apart from technologies primarily developed for the medical market, there are consumer electronics and digital solutions that find new applications in the medical sphere: gaming consoles,[1] and activity trackers[2] are just some of the many examples. With all the ongoing developments and published literature, this subject is increasingly complex. The AO Foundation's Technical Commission has established a task force to address the field of smart digital solutions concerning orthopaedic trauma care. In this regard, a smart digital solution focuses less on electronic hardware developments, and more on the processing of information as it applies to clinical use. One of the first goals is to assess the currently available technologies, their current and potential applications in orthopaedic trauma surgery and provide an overview for the modern trauma surgeon. Digital solutions are rapidly evolving, and multiple technologies will be needed to address many of the clinical needs of the orthopaedic trauma surgeon. Due to the multitude of available solutions and the changing technological landscape, categorization based on the technologies alone is not practical. An alternative strategy is to sort the available digital solutions according to the needs of the orthopaedic trauma surgeon.

The aim of this article is thus to provide an overview of how contemporary digital solutions match the needs of orthopaedic trauma surgery. Furthermore, we set out to define a suggestion of basic rules to guide the development and use of new digital solutions as they are introduced to orthopaedic trauma surgery.

Current needs in orthopaedic trauma surgery

On a broad scale, the needs in orthopaedic trauma surgery can be categorized into all phases of patient treatment, beginning with patient presentation, followed by injury diagnosis then intervention (with the sub phases of pre-, peri- and post-intervention) and finally outcome assessment.

Patient characterization

The foundation of any treatment is a thorough evaluation of the patient on presentation. Treatment is tailored to the individual patient. The patient's medical record, including previous injuries and treatments they might have received, is evaluated. Furthermore, any associated conditions and physiological baseline parameters, such as sleep, nutrition, blood tests or vital signs can determine the pre-treatment patient status. Any other relevant baseline data, such as gait analysis, activity assessment, fall-risk determination or pre-treatment clinical scoring can characterize the patient while also providing opportunities for outcome assessment throughout the treatment process. Any technology that can capture and process these types of patient information answers these needs. An example of such technologies are sensor technologies, often incorporated in wearables.

Injury diagnosis

Getting to a conclusive diagnosis is an obvious prerequisite at the start of any treatment. Traditional diagnosis in orthopaedic trauma relies on imaging findings and often the use of classification systems. However, considerably more information on different aspects of the injury can be gathered digitally. Information can be obtained at the initial contact, from emergency services, triage, continuing through the hospital management process including imaging studies and laboratory results. Technologies capable of capturing and processing such data help determine the injury diagnosis. Examples of such technologies may consist of hardware (i.e. imaging) as well as software (e.g. image processing).

Intervention

The decision on whether to treat the injury non-operatively or operatively includes data from three phases. Pre-intervention, there is a preparatory phase and decision-making process, followed at times by surgical education, patient education and implant selection or production. The intervention is a need category that is amenable to process optimization, concerning the surgeon's skills, navigation, imaging, fracture reduction or various standardization issues. The post-intervention phase consists of medical management of comorbidities, rehabilitation requirements and the assessment of compliance to aftercare measures. Technologies that contribute to optimization of these intervention phases answer the intervention need for digital solutions. Examples of such technologies include decision support systems, ePROM assessment, robotics, and augmented reality.

Outcome assessment

Orthopaedic trauma surgery advances are tied to the evaluation of specific patient characteristics, specific interventions and accurate assessment of outcomes. Digital solutions that contribute to accurate, objective and 'real-life' outcome measurement answer this need. Outcome assessment is important during the immediate, medium- and long-term aftercare process. Universally, the International Classification of Functioning, Disability and Health (ICF) of the World Health Organization can help to provide a standardized reporting of physical, mental, and social aspects of a patient's condition. Examples of outcomes in need of digital measurement solutions include fracture healing, wound healing, functional outcome, quality of life and patient-reported outcomes. Technologies meeting these needs are many. Examples are wearable sensor technology, electronic patient self-reports as well as data analysis tools that allow the exploration of large-scale registry-based outcomes data.

The following graphical representation shows our suggestion for a principal need categorization to which available technologies can be matched (Fig. 1).

Principal technologies to meet needs

Sensors

Continuous miniaturization, increasing data storage capacity and battery life, as well as cost reduction driven by widespread use in non-medical applications, has enabled various sensing modalities to become integrated into affordable body-worn devices. These are capable of assessing various parameters of interest in the context of orthopaedic trauma surgery. Movement and physical activity can be assessed using accelerometers and inertial measurement units (IMUs) containing in addition gyroscopes, magnetometers, barometers or GPS. Single or multiple sensor set-ups can generate objective data about movement quality in a routine clinical functional performance test. This can feed outcome databases, support patient stratification, generate digital movement biomarkers for advanced diagnostics or assess the quality, efficiency or ergonomics of a surgical procedure, thus feeding into all need categories previously described. Using these sensors outside the clinic, unobserved and continuously for days, weeks or longer to monitor physical activity behaviour has been generating novel, previously inaccessible digital

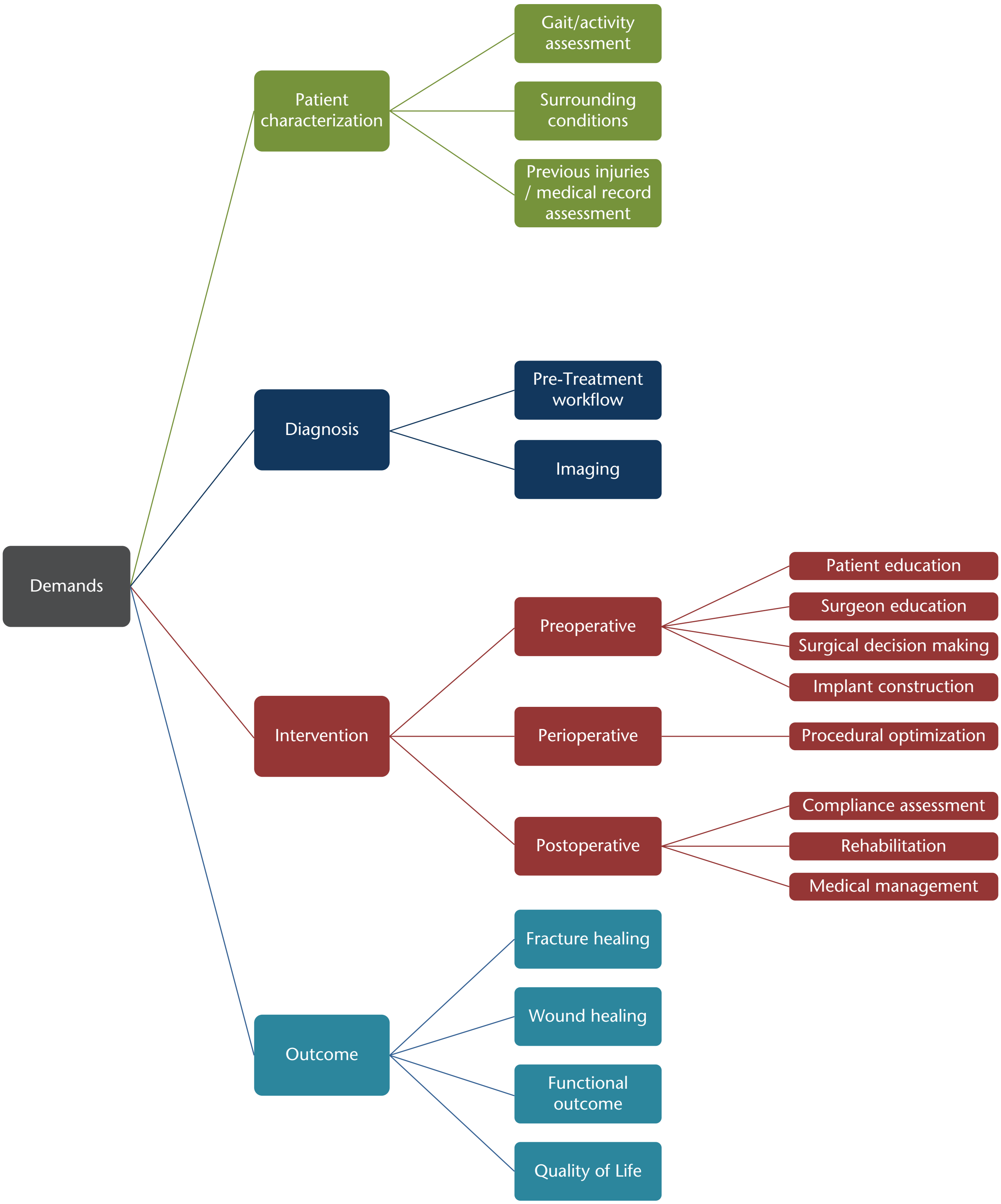

Fig. 1 Categorization of principal needs in orthopaedic trauma surgery.

outcomes about how active or inactive patients are in the real world. While step counts are widely available from consumer and wrist-worn devices, though of doubtful accuracy at the individual patient level, clinical-grade devices can classify, count and assess other activities of clinical value: stair climbing, cycling or running, cadence or turning speed are just some of the generated real-life qualitative outcomes related to fall risk or functional outcome serving patient characterization, diagnosis and outcome assessment.

By making such data accessible to the patient or their care givers as feedback, and combining it with coaching advice via a smartphone app as another enabling digital technology, wearable sensors can also become part of novel treatments and intervention addressing the need for patient involvement. The use of wearable sensors to assess physical function and monitor physical activity in elderly patients has been recently reviewed and methods and choices also apply to orthopaedic trauma surgery (OTS).[3]

Besides sensors measuring movement directly, plantar pressure insoles and heart rate sensors increasingly using optical methods (photoplethysmography) can serve specific OTS needs. Plantar pressure insoles can monitor the adherence to post-fracture repair loading protocols to optimize post-interventional care or serve as a remote indicator of the healing process. It was shown that patients cannot follow conventional postoperative loading regimes and often exceed limits traditionally considered as safe. However, compliance to such advice does not seem to influence the healing outcome.[4] Heart rate monitoring can serve the sensitivity and specificity of fall detection devices with obvious use related to OTS needs.

In a progression from wearable to implantable sensing, strain gauges attached to fracture plates can monitor the healing process via the deformation shifting from plate to bone in a characteristic profile as healing proceeds normally or abnormally. This may detect early characteristics of nonunion, thus negating the need for excess radiation exposure that sequential radiography requires. Furthermore, earlier interventions may be possible.[5]

As smartphones become ‘smarter’, incorporate more sensors and more people carry them, the phone itself can be used as a wearable sensor in the applications listed above or in innovative methods responding to OTS needs. Functional performance tests, which normally require exact instructions to the patient, can be initiated and instructed to the patient by a smartphone notification so that the analysis algorithms have the specific context to generate the desired outcome parameter required without a patient visit and thus at a higher frequency. This fused technique is also called a ‘guided routine’. In a similar fashion, objective sensor outcome can be enriched by electronic patient self-report (ePRO) collected via an app on a smartphone, enabling the link between objective outcome and subjective parameters such as pain that are not accessible by sensors. With the smartphone or any other screen-based method (PC monitor, television, tablet) as an interface to feed back sensor data or other information such as coaching advice to the patient, the treatment needs can be addressed by fall-prevention exercise programmes, rehabilitation exercise regimes or safe return to work/play testing. The fusion of sensors with other digital methods such as social media (e.g. peer group exercising) or virtual reality (e.g. exergaming) can further serve the OTS need.

Virtual reality/augmented reality

The first virtual system was introduced to medicine in 1965 and the first head-mounted display was developed shortly thereafter. This technology has constantly evolved, and is still undergoing great change today.[6,7] Although virtual reality (VR) and augmented reality (AR) share many similarities technology-wise (and are often used in the same context) VR is a completely computer-generated virtual environment, whereas AR is an overlay of computer-generated virtual content on images of the real world.[8]

The most readily available and used VR/AR technology in trauma surgery is augmented overlay of virtual hardware positioning and trajectories during navigated surgical procedures onto the intraoperative imaging.[9,10] This technology is dependent on the availability of high-quality imaging data and finds its current state of the art in hybrid operating rooms.[11] This can further be simplified by the use of head-mounted displays to relay information into the surgeon’s field of view.[12] Apart from the commercially available systems, clinically focused research in this field aims to reduce the amount of radiation exposure and markers,[13] incorporating standard systems and technologies into user interfaces and also in using AR to relay not only bony, but also soft tissue and vascular anatomy to the surgeon’s field of view.[14] Apart from intraoperative use, this technology can also be used for surgical planning with VR and AR assisted planning of reduction and hardware position, as well as hardware templating in a virtual environment.[9,15] Furthermore, virtual reality solutions have been proposed for use during pre-intervention patient education,[16] gait training and fall prevention and also post-injury/post-intervention aftercare. In the rehabilitation phase, patients can be AR/VR exposed to visual stimuli emulating challenging situations in a safe environment (e.g. Motek system).[17,18] In addition to these clinical uses, AR/VR technology has a strong foundation in surgical education both creating full VR environments, and also augmenting real-life situations.[7,19] As a synthesis of teaching and treating, AR systems to allow remote surgical assistance have been proposed.[20]

Data science and clinical decision support systems

Large amounts of digital information are being constantly generated on our patients and are also readily available for analysis. This ‘digital footprint’ includes data available from electronic medical records (EMR), social media, biometric data from patient wearables, registry data, imaging data, genomic data and more. The need to manage and derive meaningful use of this digital information resulted in the growing importance of the scientific field of data science.[21]

Data science can be thought of as a merger of statistics with computer science, specifically aimed at 'exploiting the modern deluge of data for prediction, exploration, understanding, and intervention'.[22] Data scientists use multiple techniques to arrive at meaningful use of available data. These techniques include: data exploration and preparation, data representation and transformation, computing and modelling data, and data visualization and presentation.[23] Modelling in data science involves traditional academic statistics and its offshoots (generative modelling), as well as modern machine learning and its offshoots (predictive modelling).[24] Clinical Decision Support Systems (CDSS) are algorithm-based software applications that are typically integrated into EMR systems and analyse specific patient information in order to provide clinicians with evidence-based recommendations on treatment.[25]

Data science applications are becoming increasingly more common in medicine in general and in musculoskeletal medicine and orthopaedic traumatology in particular. At the most basic level of a CDSS are online calculators such as American Academy of Orthopaedic Surgeons (AAOS) Appropriate-Use Criteria (AUC) for acute treatment of hip fractures in elderly patients.[26] These tools make use of evidence-based literature and expert panel scoring of different clinical scenarios to generate patient-specific treatment recommendations.[27] In using online AUC calculators, clinicians are required to collect and enter patient-specific information into the system. More sophisticated CDSSs are fully integrated into the EMR, making their patient-specific recommendations automatically. Such systems were shown to be successful in reducing venous thromboembolism in surgical patients.[28] Traditional CDSS relies on evidence-based medicine (EBM) to generate an algorithm which analyses patient-specific data. Newer data science techniques involving machine learning use patient data to build predictive models that are not directly related to classical EBM. In complex patients, such as those suffering from polytrauma, this approach may turn out to be more effective in predicting the results of interventions in the specific patient.[29] Such data science approaches have been used to predict infection risk[30] and mortality[31] in intensive care unit patients with blunt trauma. Other data science approaches are likely to gain a presence in clinical trauma care in the near future. These include machine learning based image analysis software to diagnose and classify fractures,[32] optimize cost of trauma care,[33] reduce surgical risk[34] and predict postoperative pain.[35]

Robotics

Robotic technology is rapidly developing, and we increasingly look to these solutions for complex orthopaedic problems. There are different types of robots which have been used to date, and these can be differentiated by the amount of autonomy granted to the robot as well as the type of feedback given to the surgeon (none, boundary or haptic). In orthopaedic practice, robotic technology has gained the greatest amount of acceptance in hip and knee arthroplasty. Beginning with the Robodoc/TSolution One (Think Surgical) and followed by Mako (Stryker), Navio (Smith and Nephew) and now Rosa (Zimmer Biomet), these robots have gained a stronghold by demonstrating fewer outliers in total knee[36] and hip arthroplasty,[37] with improved short-term revision rates reported for unicompartmental knee arthroplasty.[38] While the Mako, Navio and Rosa rely on boundary control and haptic feedback for saws (Mako), burrs (Navio) and jigs (Rosa), the TSolution One uses autonomous control by the robot, which completes a preoperative plan. While a significant learning curve has been consistently reported with adoption of this technology,[39,40] complications from the use of the robotic systems are rare.[41] To date, no long-term studies have been conducted to determine whether robot use leads to better patient-reported outcomes.

Recently, robotic technology has begun to be more widely used in spine surgery, where pedicle screws can now be inserted with robotic assistance. To date there are three robots commonly utilized in spine surgery: SpineAssist (Mazor Robotics), Rosa (Zimmer Biomet) and Excelcius (Globus Medical). These robotic systems have demonstrated increased accuracy with pedicle screw placement when compared to open freehand technique.[42,43] Along with this, there is evidence that there is reduced intraoperative radiation exposure compared to both navigated and fluoroscopic guided insertion.[44] This finding is most relevant to the operative team, as all of these robots require a preoperative CT scan. Much like robot use in hip and knee arthroplasty, there is a significant learning curve associated with its use in the spine. One study demonstrated that the time needed for pedicle screw insertion decreased from 5.5 min to 4.0 min ($p = 0.23$) after the first 15 cases.[45] To date there is no data demonstrating improved patient-reported outcomes with the use of robotic technology in the spine.

The use of robotic technology in orthopaedic trauma is currently in its infancy. There is one robot, TiRobot (TINAVI Robotics, Beijing), which has been used in the orthopaedic trauma setting. This robot uses intraoperative imaging and acts as an aiming device for wire placement in procedures amenable to percutaneous fixation. This includes scaphoid fractures,[46] pelvic fractures[47] and femoral neck fractures.[48] In one study looking at percutaneous screw placement for femoral neck fractures, use of the robot resulted in decreased fluoroscopy time, operative time, and improved screw trajectory when compared to a standard fluoroscopic technique.[48] Unfortunately, this technology has yet to become available in the American and European markets, and further work is needed to validate its effects on patient-reported outcomes.

3D printing

The foundation of 3D printing is a high-quality three-dimensionally useable image data stack obtained either from computed tomography (CT) or magnetic resonance imaging (MRI) or from specialized computer software.[49] Commercially available computer aided design (CAD) programs can use this data to generate models and templates and, after further adaptation, convert the imaging data into printer-readable outputs (most commonly standard triangulation language/STL) for use with 3D printers.[50] Printers use different synthetic or metallic substrates to generate the predesigned models in an additive fashion, tailored to the predetermined biological, physical and chemical requirements.[49,51]

To classify the uses of 3D printing in trauma surgery, Krettek et al have suggested six stages of application for this technology.[49] The first stage uses 3D printing to simply generate bone models which help clinicians to better understand fracture patterns and demonstrate the injury to the patient.[52] The second stage is the use of 3D print output as tools/instruments, to assist with implant pre-bending,[53] with reduction,[54] as cutting or drilling templates[55–58] ('template guided navigation'[49]) and also to aid in the production of orthotics or prosthetics after amputation.[59,60] Stage three is using the 3D print as the actual implant to provide a patient-specific and individualized solution, which can also assist with reduction.[61,62] The fourth stage is the use of 3D printing to provide a matrix for structural bone deficits or as a scaffold to be coated with other materials/agents (i.e. antibiotics). Stages five and six are tissue prints and hybrid/composite prints of different tissues and materials.[63,64] 3D printed solutions have been described for almost every bone and joint: acromion,[65] clavicle,[53,66] glenoid,[62] humerus,[58,61,67–69] radius,[56,70] pelvis,[71–74] spine,[75,76] femur,[54,55,77–80] tibia,[81–85] calcaneus,[86,87] talus,[88] and the ankle.[57]

Imaging/navigation

Orthopaedic trauma surgery is dependent on intraoperative imaging. The implementation of the flat-panel technology in either fixed or mobile c-arms increases the image quality and can reduce the radiation dose.[89–91] Additional benefits include an increased field of view, a larger 'source to detector distance', asymmetric collimation and even motorized steering of the c-arm.[89] This technology can also be used for intraoperative 3D visualization. Therefore, the flat-panel c-arm rotates around the region of interest generating a 3D volume out of a large number of single images.[89] The shape of the beam lead to the nomenclature 'cone-beam-CT'. Their high image quality and large visualization volume enables immediate control of reduction and implant position, which can reduce the incidence of revision surgery.[92] Furthermore, the reduction of the injured side can be compared to the uninjured side in the operating room (e.g. pelvic ring fractures). Radiation dose is mainly dependent on the region of interest and the protocol used.[93] Cone-beam-CT scanners have been most widely used in spine surgery, but the availability in the OR of these systems has led to new applications especially in orthopaedic trauma surgery. They can be an essential help in complex anatomic regions and joint fractures.[94] Intraoperative 3D image acquisition can also be obtained through the use of a fixed or mobile fan-beam-CT. They ensure a high image quality, but lack the possibility of intraoperative fluoroscopy. The primary area of application is in spine surgery, but it can also be used for other anatomic regions such as the pelvis.[95,96]

All of the mentioned imaging devices can be combined with a navigation system, which can be used in 2D or 3D. However, 3D navigation seems superior compared to 2D navigation, especially in the spine or the pelvis.[97] After an intraoperative 3D scan or CT the data is transferred to the navigation software. In most systems, screws can be planned and implanted according to the stored trajectory with the help of an optical or infrared camera. This can also be performed with a preoperative data set. Intraoperative navigation assures a high accuracy of reduction and implant placement in spine and pelvic surgery.[98,99] It can also be valuable in orthopaedic tumour resection, helping the surgeon to define the correct resection borders.[100] A combination with robotic drilling and placement tools is possible. Moreover, navigation can lead to a reduction of intraoperative radiation.[101]

A new method of navigation is the use of templates, which are 3D printed preoperatively according to a 3D data set. They are positioned during surgery according to the anatomy of a specific vertebra/spinous process and allow only a predefined drill direction and therefore screw position is highly accurate.[102]

Social media

You cannot go anywhere in the world without encountering people using social media. This also applies to medicine and orthopaedic trauma surgery. For the purposes of digital solutions in trauma surgery we must differentiate social media tools focused on medicine and trauma surgery from those designed for public use. These public tools are mainly used in orthopaedic trauma for patient education and presentation of procedures and treatments available at certain locations. Most commonly, hospitals and private practices alike present their offered treatments in text, image and video form. Moreover, social media is increasingly used for patient polls and study recruitment wherever local laws allow. Care must be taken to protect patient privacy whenever social media is used for practice promotion. Furthermore, there is the emerging research methodology on monitoring social media activity by patients to derive their outcome by the frequency and type of social media engagement and interactions. Ultimately, it is a tool to communicate with patients, individually or on group level, to collect input for patient-focused developments increasingly demanded by funding bodies. Social media also allows for patients to organize themselves and communicate with each other offering peer-to-peer exchange of information about the clinical pathway, which may be a tool for patient empowerment, but is also an uncontrolled space with the risk for misinformation.

Apart from the known public tools, there is an increasing market of medical and surgical social media tools. These tools address three different needs for the trauma surgeon covering primarily educational aspects related to all four OTS needs. The first category is aimed at physician collaboration, with platforms specifically addressing trauma, such as the AO Interact website (https://www.aointeract.org), which offers a platform for surgeon-to-surgeon multimedia education with messaging functions and the option to formulate open questions that can be answered by fellow AO surgeons. Secondly, there are the websites aimed at surgeon physician education, either primarily through text and images, such as orthobullets (https://www.orthobullets.com) or the AO surgery reference website (https://www2.aofoundation.org/wps/portal/surgery) or through videos with websites such as vumedi (https://www.vumedi.com) and other dedicated video streaming channels. Furthermore, websites such as orthobullets also offer extensive test preparation and study tools. Finally, there are websites aimed at scientific collaboration and distribution of published works. The most prominent of these is researchgate (https://www.researchgate.net).

The mobile smartphone

Undoubtedly the most widely distributed technology in the general and medical population with applicability in orthopaedic trauma surgery is the phone or smartphone. First and foremost a tool to communicate and obtain information through calls and the internet, it also has very specific uses in trauma surgery that concern all aspects of treatment from the pre- and peri- to the postoperative phase. The smartphone is a now ubiquitous personal device offering computing power, a screen, multiple sensors and wireless connections, technologies which serve OTS needs as described above (wearable sensor assessment, VR/AR device, social media interface, etc.) or enable additional solutions.

Preoperatively the phone can assist in and improve layperson care for trauma patients all the way to assisted resuscitation and care dispatch[103] by providing instructions which are always readily available. Additionally, it can be an educational tool for the patient aiding in risk assessment and understanding a planned procedure[104] and the clinical pathway. For the surgeon, these devices provide access to mobile applications which have shown improved patient care with use for common trauma injuries,[105,106] video streaming of lectures, conferences and direct feedback and teaching from peers, also through electronic participation for journal clubs and grand rounds.[107] Furthermore, it can be used to aid decision-making regarding soft tissue injuries, replantation indication and fracture care,[108–113] with studies already available on the diagnostic precision of radiographs transferred via the phone.[114] This is especially important in rural areas, where expert medical assessment might not be available immediately, but the patient's injury needs a rapid decision.[111,115] However, diagnostic accuracy can be reduced compared to in-person consultation.[116]

Perioperative use of the phone can again be used for emergency consultation purposes, to aid in the treatment process with phone applications such as the AO surgery reference tool depicting common trauma surgeries step by step, including patient positioning and approach,[117] and simply to access imaging information.[104] Postoperatively, the phone can be used to provide digital follow-up visits,[118] assist with patient evaluation and measurements[119,120] and also to provide guided rehabilitation with biofeedback.[121]

Additionally, the phone is a device that encompasses many of the previously mentioned technologies. It can be a sensor to measure gait and activity,[122] with many commercial solutions allowing for a pre-injury activity state determination, it can be a VR/AR device for clinical and educational purposes,[123,124] provide clinical and radiographic imaging[104] and, most importantly, is the main tool to engage in social media with.

Discussion

Meeting the needs

There are many needs for digital solutions in orthopaedic trauma and a lot of principal technologies available to address them. In an effort to identify the needs and technologies relevant to trauma surgery, the AO Foundation's Technical Commission has instituted a task force, assigned in part to provide an overview of this broad field and structure the rapidly growing technologies and applications to guide their meaningful selection, evaluation or new innovative developments. This article and the matching of available technologies to current needs as the clinically most meaningful criteria are the result of the inaugural meeting of this task force and are a consensus between the authors gathered with a nominal group technique (see Appendix).

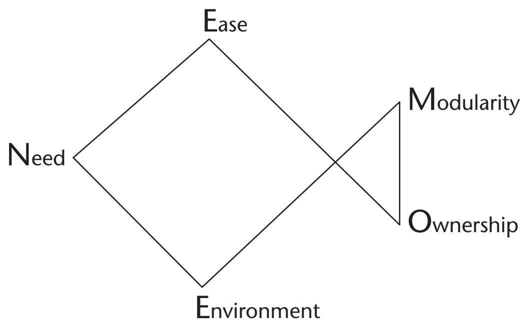

Fig. 2 NEEMO guiding framework.

Guiding principles for developing and using trauma-relevant technology: the NEEMO framework

The application of digital solutions in a medical context requires certain prerequisites and compliance with regulations that ensure the technical product qualifications. These are specified by strict national medical device regulations and are not part of this article. Apart from these mandatory laws there are additional principals that many surgeons instinctively apply to guide their application of these tools for research and patient care. Based on their own experiences and discussions with peers, the authors have drafted and refined the following guiding principles to aid developers, researchers and clinicians using digital solutions to address their needs. These principals can be seen as ideal attributes for a digital solution in orthopaedic trauma, and can be abbreviated with the acronym NEEMO (Fig. 2).

Need

The first prerequisite seems like common sense, in that a digital solution should address a clinical need in order to be relevant to trauma surgery. However, many tools introduced as part of this article were developed with different needs in mind than those relevant to the care of trauma patients. Commercially available activity sensors, VR/AR hardware, 3D printing and social media or mobile phones are just some of them. Yet these tools can be successfully utilized during the immediate or extended care of injured patients. For this reason, this prerequisite can be important during the development of specialized solutions, but is most relevant before starting a research project or clinical treatment. As laid out in this article, the clinical need is the first step to determine which solution can best serve the intended purpose.

Ease of use

This is a vital factor to ensure broad clinical application of a new technology or adherence to its use. While this is certainly a subjective criterion it is also formally accessible through usability analysis[125–127] and thus a factor that developers should bear in mind or conduct usability research, as this will influence the use of certain tools in broad clinical application. While a research tool can be developed for a more technology competent population this principle still applies, and overly complicated tools risk a decrease in compliance of both the researcher and patient. An example for the importance of this principle is the use of gait analysis in standard trauma care: while great research has been performed with large, stationary gait labs, their use in everyday clinical treatment centres is limited due to the many obstacles in using these tools, with their cost, set-up and required expert knowledge just to use these tools being the most important.[128] The advent of tools that are easier to use and the availability of commercially available tools to assess general activity through sensor technology, however, have led to an increased use of gait analysis during clinical treatment.

Environment for gathered data

Data should be stored in a safe and accessible environment. One part of this is that the entire process of data acquisition, transfer and storage is in compliance with data safety regulations. Another part is that as a principle of good practice increasingly demanded, i.e. as part of the Clinical Trials Transformation Initiative,[129,130] the raw data obtained is available to the clinician and researcher or, if onboard modulation of data is performed, that this process is made transparent to ensure comparability to other devices.

Modularity and portability

Data generated from digital technology should be modular and portable in the sense that it can be combined and incorporated into different platforms for analysis. This ties directly into the data environment aspect. Tackling the needs of modern trauma surgery often requires a variety of technologies. It only makes sense that these technologies will be able to interact with each other. In addition, the benefits of data science methods are only accessible when the generated data is compatible and labelled or when big data can be collected from various devices. When developing, but also before starting to use a new product, the trauma surgeon should be mindful of this prerequisite as it can influence the usability of other technologies or transferability of results.

Ownership of data

For some of the technologies this is not relevant as long as the data produced is only stored locally, never transferred and remains only with the clinician or researcher. However, some technologies, especially wireless sensor tools and mobile applications, store their data remotely, and data ownership can be an issue when it comes to compliance with national data safety regulations or funding regulations for clinical research. Trauma surgeons have to be mindful of this whenever choosing a technology to meet their need.

A final thought

In the end, whatever the new technology and solution concerning a specific need in trauma surgery might be, the key to improving patient outcomes will be to have tools that follow the NEEMO principles and are widely distributed. From the surgeon's side, instead of being 'wedded' to just one product, the key to success will be to combine multiple NEEMO-adherent products. The modularity and portability aspects of these technologies will allow for more holistic digital solutions. An elegant approach, especially in the field of sensor technology, would be not to force a research system on the patient, but rather to be able to use a technology that the patient already has, such as fitness trackers, which are widely prevalent in the younger patient population today. With this approach, the ambitions of personalized medicine will be easier to achieve, as this would not only increase compliance of use, but most importantly allow for assessment of individual fitness and activity level prior to the injury (pre-trauma 'activity biopsy'). It would offer the opportunity to determine the true, objective and individual healing outcome compared to the pre-injury activity level.

In conclusion, there are many technologies already on the market addressing a multitude of needs in orthopaedic trauma surgery, and this market is likely to change significantly in the future. In that sense, an article such as this one can never be complete. In the time it takes to go through the publishing process alone new solutions will be published and developed. The goal of this article is to give a brief overview of the existing digital solutions as they pertain to the needs of orthopaedic trauma surgeons. We also provide a structure to sort and make sense of the abundant number of available solutions to help the user navigate this growing field using a need-driven compass. Finally, we suggest that adherence of future technology (and its adoption by orthopaedic surgeons) to the NEEMO framework will greatly increase its usefulness and adoption into clinical practice and medical research.

AUTHOR INFORMATION

[1]Department of Trauma, Hand and Reconstructive Surgery, Saarland University Hospital, Germany.
[2]Luxembourg Institute of Health, Luxembourg.
[3]Los Alamitos Orthopaedics, Los Alamitos, California, USA.
[4]Department of Orthopaedic Surgery, University of California, San Francisco, California, USA.
[5]Weill Cornell Medical College, Foot and Ankle Surgery, Downtown Orthopedic Associates, New York Presbyterian Lower Manhattan Hospital, New York, USA.
[6]Orthopaedic Surgery, Pantai Hospital Kuala Lumpur, Malaysia.

Correspondence should be sent to: Benedikt Johannes Braun, Department of Trauma, Hand and Reconstructive Surgery, Saarland University Hospital, Building 57, Kirrbergerstr. 1, 66421 Homburg, Germany.
Email: benedikt.braun@uks.eu

ICMJE CONFLICT OF INTEREST STATEMENT

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