Bridging Gaps in Fracture Rehabilitation: A Mobile Solution Proposal for Comprehensive Recovery

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Abstract: This paper explores the prevalent challenges associated with musculoskeletal injuries across various demographics. It proposes the idea for a comprehensive mobile application designed to improve post-fracture aftercare by addressing existing gaps in information sharing, personalization, and remote care. Comprising three core components – recording and assessment of physiotherapy exercises, physical load measurement at the fracture, and a shared documentation tool for all participants involved in the aftercare process – the system aims to enhance patient compliance and improve recovery outcomes. The system will then be evaluated technically with healthy subjects to validate the system components. Subsequent usability evaluations will involve feedback from both healthy subjects and potential end-users, paving the way for planned clinical investigations with patients undergoing ankle fracture treatments to assess system efficacy, patient-reported outcomes, and compliance.

1 INTRODUCTION

Musculoskeletal injuries are prevalent among individuals in Germany aged 65 and above (Fuchs et al., 2013), often necessitating surgical interventions. These injuries frequently result from falls among elderly individuals (Kannus et al., 2002) and require extended recovery periods. Respecting the demographic shift, the frequency of such injuries is expected to further increase. Not only elderly people suffer from musculoskeletal injuries, also younger individuals experience such injuries with an increasing frequency (Rupp et al., 2021), particularly after accidents, constituting a significant cause of work-related absences (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2022). Beyond the impact on the quality of life, these injuries result in substantial healthcare and socioeconomic costs, including expenses for surgical procedures, compensation for disability leave, early retirement, rehabilitation measures, and reduced productivity.

The quality of post-injury care is an essential factor for the success of the healing process. A good quality can encourage a quick relief, full recovery of the disease and is able to prevent further complications. The predominant factor influencing the overall expenses in patients with fractures and non-unions is indirect costs, such as productivity-related losses (Hak et al., 2014). Post-injury care encounters several challenges in the current healthcare system. This includes for example the insufficiently addressing of prescriptions. Elderly individuals frequently receive equivalent exercises and repetitions in physical therapy following injuries, similar to younger patients. (Teng et al., 2012). For a successful and fast recovery of patients after musculoskeletal trauma surgery, the patient requires individual treatment and therapy by multiple healthcare professionals including surgeons, general physicians and physiotherapists (Figure 1). For an optimal multi modal, holistic and in-

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dividual treatment, information about patients' recovery should be shared and discussed by the involved healthcare professionals. However, studies indicate that there still seems to be a lack of connectivity between healthcare professionals (Reeves and Zwarenstein, 2017). These shortcomings in patient centred care lead to partially contradictory advice, which cannot be comprehensively processed by the patients due to insufficient expertise.

After being discharged from the hospital, surgeons generally receive limited information about the patient's recovery progress unless a subsequent operation is necessary. Physiotherapists customise exercise regimes to suit individual patients, however, they only receive subjective feedback once or twice a week. To date, there has been no exchange of information between physiotherapists and other healthcare professionals in Germany to adjust treatment. If a re-injury takes place or if the process of recovery diverges from expectations, it can prove to be exceptionally disappointing for all those involved in the post-injury care process. Insufficient communication often leads to a failure in documenting the fundamental reasons behind such setbacks. Noncompliance with the healthcare professionals' instructions, incorrect instructions for specific patients, or errors in the initial surgery may all contribute to this uncertainty. Therefore, achieving full recovery from such injuries hinges on patient compliance with daily exercises, requiring motivation, education, and dedication of patients and supervision, monitoring and coaching by health care professionals. Due to the short and limited therapy sessions, this supervision, coaching and monitoring is often lacking, fostering insecurity among both doctors and patients regarding the durability of the fracture.

An example demonstrating the importance of tailored exercises and supervision during post surgery treatment of musculoskeletal fractures is the weight-bearing during recovery. The weight-bearing aspect within post-care after getting a fracture injury remains a contentious issue, as patients often have only a rough estimate of the compression they can safely apply to the affected body region. This is especially valid for geriatric patients that often struggle to maintain the set weight-bearing restrictions (Kammerlander et al., 2018). Commonly used training methods for weight bearing, for example using household weight-scales to define the load, neither show good short-term nor long-term learning effects of the prescribed limits (Dabke et al., 2004) (Braun et al., 2017). Poorly managed weight-bearing during different phases of post-injury care can have adverse consequences on the long-term healing process, underscoring the importance of effective communication and measurement of these parameters.

Another aspect of individual care after musculoskeletal injury is the need for more adaptable options for participating in physiotherapy. This requirement has become less pressing since the outbreak of the COVID-19 pandemic, as scheduling appointments proved challenging during times of restricted human contact. For instance, attending physiotherapy sessions in person often necessitates the assistance of family members due to the patient's limited mobility. In addition, elderly people and patients with jobs requiring traveling or or having an irregular daily working life benefit from a solution that makes remote training sessions and exercises possible in an independent setting full of flexibility. The reduced availability of healthcare facilities in rural areas (Kassenärztliche Bundesvereinigung KdöR, 2022), combined with ongoing shortage of skilled workers (Bundesagentur für Arbeit, 2023), further fuels the demand for methods that enable home-based physiotherapy. Nonetheless, existing online physiotherapy methods can be challenging due to the need of therapists to demonstrate exercises in front of a camera while looking at the screen at the same time. Moreover, ambulatory physiotherapy approaches must be thoughtfully considered to ensure patient compliance and maintain the same level of efficacy as in on-site physiotherapy. "Its worth noting that correctly executed digital physiotherapy has the potential to be just as effective or even more effective than on-site physiotherapy." (Lara-Palomo et al., 2022) (Weise et al., 2022).

In summary, we have identified three primary challenges within the current post-fracture aftercare process we aim to address in this research:

1. How can we enhance the effectiveness and adherence of digital physiotherapy as compared to current literature?
2. How can we facilitate patient awareness of the weight-bearing restrictions associated with their fracture?
3. How can we enhance the documentation process to facilitate the sharing of pertinent aftercare information among all stakeholders involved?

The following chapters are structured as follows: Firstly, we outline our contribution and discuss current related literature in section 2. Then we present our method for addressing the research questions mentioned above in section 3. Finally, we present our findings. This is followed by a description of the methodology in section 4. Our goal is to conduct extensive research to determine the effect of our application on post-injury recovery. We compare the af-

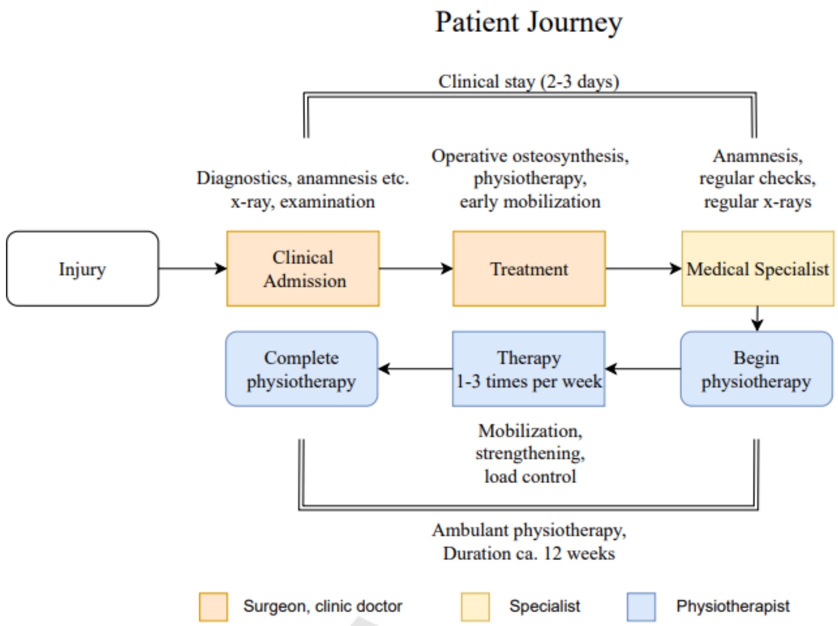

Figure 1: The diagram depicts a common pathway for patients following an ankle fracture and the stakeholders associated with each stage. Following a hospital stay for up to three days, the patient is referred to a specialist who conducts periodic examinations and x-rays on the injured area. The patient then undergoes physiotherapy for roughly twelve weeks with varying phases of load management.

tercare process to conventional practices in section 5, providing an objective evaluation. In addition, section 6 presents a conclusion and outlines potential future work.

2 RELATED WORK

Research into the usability of mobile applications to assist physiotherapy has gained significant importance, particularly in light of the COVID-19 pandemic. Kasnakova et al. conducted a pivotal study demonstrating that the utilization of mobile health applications can substantially enhance the rehabilitation process (Kasnakova et al., 2022). Moreover, there are already various systems available to assist patients with at-home exercise programs. For instance, Komaris et al. assessed an IMU-based system designed to ensure the correct execution of physiotherapy exercises during unsupervised treatments (Komaris et al., 2022). Others have explored intricate 3D motion capture systems (Mousavi et al., 2020) or offered disease-specific information and structured training schedules to enhance exercise accuracy (Thiengwittayaporn et al., 2023). Weber et al. introduced a smartphone-assisted training system that fosters the repetition and consolidation of learned exercises by facilitating audio-visual communication between patients and physiotherapists (Weber et al., 2023). A review of current literature reveals a variety of exercise evaluation tools based on motion tracking or inertial measurement units (IMU) to assist patients. However, we propose an experimental approach by employing a neural network for the evaluation of exercise correctness and repetitions. Importantly, this approach would not require a complex setup and is therefore more suitable for at-home assessments. Our approach leverages marker-less motion capture technology using standard 2D cameras, readily available in patients' smartphones, tablets, and laptops.

In the domain of load measurement systems in physiotherapy, Braun et al. conducted a survey in 2018 to explore the usage of measurement instruments by physiotherapists in Germany (Braun et al., 2018). Their findings indicated that physiotherapists generally have a favorable view of using measurement instruments, provided that there is financial compensation for acquiring them. Notably, the prevalent approach in research involves insole measurement systems, which are already applied for gait, load, and activity analysis (Braun et al., 2016). By integrating the measurement system into the patient's implant, we aim to eliminate the need for additional tool purchases and ensure the continuous availability of load data.

Regarding documentation tools for aftercare, Griefahn et al. conducted a Delphi study to assess the potential benefits of digitization in the documentation processes of physiotherapists, outlining specific requirements for such an application (Griefahn et al., 2020). Building upon this study, our objective is to create a more standardized documentation process that actively involves all stakeholders while maintaining a degree of flexibility.

Finally, we would like to emphasize that the integration of these three components – mobile applications to support physiotherapy, load measurement systems, and documentation tools for aftercare – represents a promising innovation. To the best of our knowledge, such a combination has not been extensively explored to date. We believe that this holistic approach has the potential to significantly enhance the efficiency and effectiveness of physiotherapeutic care.

3 CONTRIBUTION

In this work, we propose a comprehensive mobile application that tackles the aforementioned problems. Our primary objective is to enable individualized, self performed and (at least partly) automatically supervised training and rehabilitation exercises. Our secondary objective is to equip patients with a tool to monitor their weight-bearing and warn them if they exceed the set limits. The third objective of this project is to facilitate seamless data exchange between physicians, physiotherapists, and patients, streamlining and individualizing the aftercare journey. By addressing the existing gaps in information sharing, personalization, and remote care, our system aims to not only enhance the quality of post-injury care but also foster patient compliance, ultimately resulting in improved recovery outcomes.

Our system is structured into three core components shown in Figure 2, each offering a dedicated interface for different users:

1. Recording and Assessment System for Physiotherapy Exercises: This component serves as a comprehensive solution for exercise recording and evaluation. Physiotherapists can easily record exercises using a standard camera, whether a smartphone or webcam, or select from a pre-defined library of exercises and customise them with individual patient annotations. These video recordings are employed to train a neural network, which then assesses exercise execution for correctness. Using marker-less motion tracking technology, the system generates a 3D avatar demonstrating the exercise on the patient's tablet or smartphone. AI algorithms dynamically adjust the camera angle to provide the most optimal view based on the specific exercise. The effectiveness and adherence of the system is then being evaluated.

2. Load Measurement System: This system is used for real-time monitoring and assessment of the physical stress on the affected area, and alerts the patient in the event of overexertion. Healthcare professionals can access a graphical representation which illustrates the linkage between physical strain, exercise regimes, and the pain reported by patients. This integrated view promotes more informed decision-making concerning the suitability of exercises for each patient's distinctive situation.

3. Shared Documentation Tool: A collaborative platform facilitates all stakeholders involved in the aftercare process to access and update relevant treatment-related data. Such information encompasses data obtained through exercise evaluations and load measurements. Moreover, the tool functions as an appointment prompt for patients, providing them with an overview of their present condition and outlining the subsequent steps in their recovery process, thereby serving a motivational purpose.

4 METHODOLOGY

4.1 Exercise Recording and Assessment

In our primary stage, we will concentrate on setting up the tool for exercising and assessment. Although our application has the potential to cover various fractures with similar post-injury care regimens, we have chosen to use an ankle fracture as a representative example for exercises and studies. Ankle fractures are of special interest in this context as the recommended exercises often involve delicate movements of the leg and foot, which can prove difficult to identify using motion capture tools. Consequently, any approach capable of assessing these exercises must also have the capacity to identify more complex movements. The aftercare for ankle fractures typically comprises three phases, each varying in duration depending on the patient's progress: the initial stage involves no weight-bearing, the second stage introduces partial weight-bearing, and the third stage permits full weight-bearing adapted to pain levels. In collaboration with physiotherapists in the team, we have selected two exercises for each stage, resulting in a total of six exercises that patients with ankle fractures typically perform during their post-injury recovery program.

Our primary objective in this stage is to display an avatar demonstrating these exercises on the patient's mobile device as seen in Figure 3. Physiotherapists should have the ability to record their exercises or select from a library of pre-recorded exercises. To facilitate exercise recording, we require a motion-

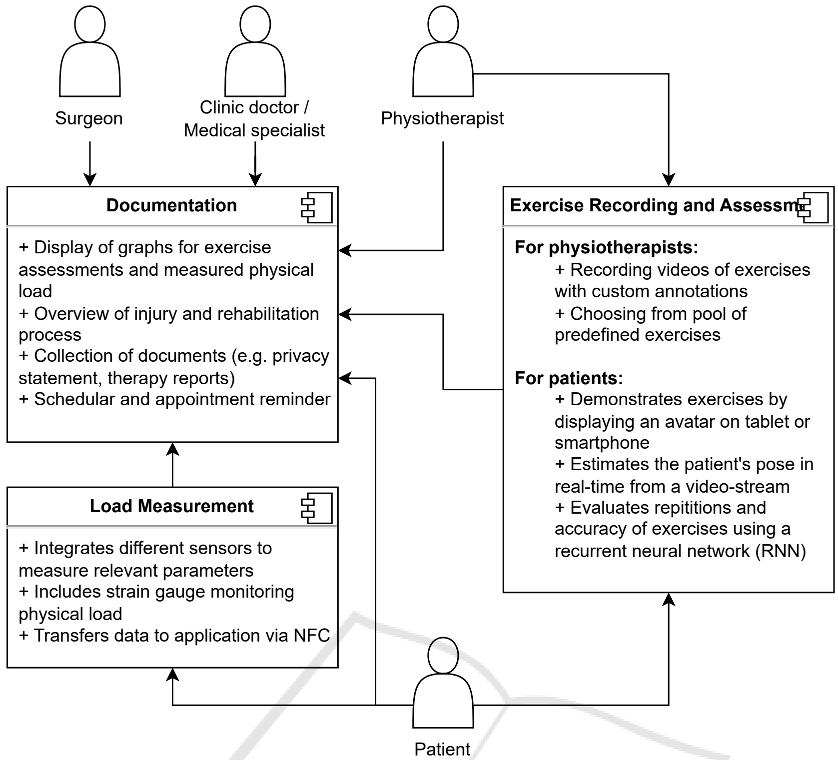

Figure 2: The graphic gives an overview of the components planned in our application. The physiotherapists get access to an exercise recording tool which is then used as the basis for the exercise assessments done by the patients. The documentation tool gathers the data collected by the exercise assessments and the load measurements and offers further functionality such as a collection of documents and a scheduler and appointment reminder.

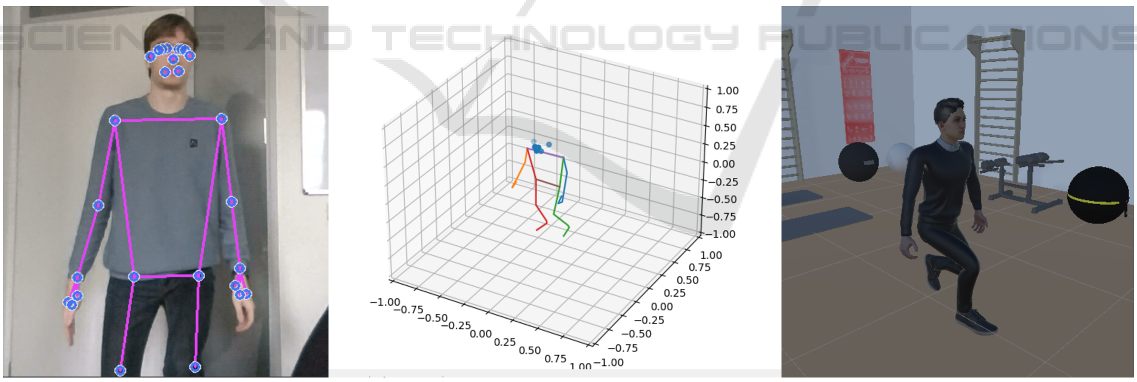

Figure 3: The graphic displays the estimated joint coordinates in a 3D space on a scale from -1 to 1 as estimated by MediaPipe. We used a standard webcam to record a squat here (left side). On the right side, there is an example of the animation for another recorded exercise that could be enriched with additional information by the physiotherapist and displayed to a patient.

capture tool. We consider two established open-source libraries, MediaPipe developed by Google and OpenPose, which is a library developed by a group of researchers and is free for commercial and non-commercial use (Cao et al., 2017). Both libraries are capable of identifying and tracking key body landmarks in real-time video, such as those obtained from a 2D camera stream. This technology allows to convert a video stream into a sequence of joint positions for each frame, with a target frame rate of approximately 20 images per second to ensure precision in capturing even subtle movements. First experiments with MediaPipe have shown that utilizing MediaPipe for ankle joint detection poses a considerable challenge as subjects need to be fully captured within the camera image, introducing potential deviations. This difficulty arises from MediaPipe's reliance on only three coordinates in the ankle and feet area, impacting the precision of joint detection. Therefore, our proposed solution involves integrating the pose estimation capabilities of MediaPipe with a straightforward 2D camera detection of joint angles. This hybrid approach aims to enhance the reliability of ankle joint detection and address the limitations associated with using MediaPipe alone.

By applying inverse kinematics, we can determine the joint angles required to achieve the desired position, creating a fluid animation of the recorded exercises that can be applied to any character model with a humanoid skeletal rig. Adobe's Mixamo provides a robust platform for character animation and rigging, offering pre-rigged characters that are free to use. Our goal is implementing animations for various 3D characters of Mixamo, enabling patients to select their preferred avatar.

Another important objective is the detection and assessment of patients' exercises, primarily focusing on two metrics: First the number of exercise repetitions and second the alignment with the therapist's example. To achieve this, we intend to train a neural network with the joint angles obtained from recordings of exercises demonstrated by physiotherapists. Specifically, we intend to apply a recurrent neural network (RNN) to identify patterns and repetitions in exercises. Recognizing that patients and physiotherapists may perform exercises with variations or different orientations to the camera system, we intend to establish joint angle limits for each exercise, which will be included in the training dataset. Rather than seeking exact replication of exercises, we will prioritize determining whether a movement exceeds joint angle limits (indicating potential harm) or falls below the threshold of necessary motion (indicating ineffectiveness). To gather a substantial amount of data, physiotherapists shall document and classify ten iterations of each movement.

4.2 Load Measurement

In the subsequent stage, we will introduce a measurement system to assess the physical load on the fracture. Initially, we equip a stabilizing sleeve with different sensors to measure relevant parameters at the fracture like the physical load or the range of motion. An integrated sensor will be utilized to closely monitor load levels at frequent intervals. The recorded data will be seamlessly transferred to a documentation system and displayed on the patient's smartphone or tablet. Our ultimate objective is to integrate a strain gauge technology into an implant and to combine the measurements of multiple sensors into an holistic measurement of the load affecting the fracture. However, due to regulatory constraints that necessitate medical approval for implants, we will also measure the ground reaction forces using insoles in our initial studies. We will subsequently compare the recorded forces obtained from the insoles with those obtained from our experimental system, allowing us to assess the performance and accuracy of both measurement methods.

4.3 Documentation

The final component of our application will combine stress measurement data and exercise assessments into a comprehensive documentation system with separate views and permissions for doctors, physiotherapists and patients. Additionally, the system will incorporate essential documents, such as therapy reports and the patient's privacy statement, ensuring that these documents only need to be completed once. Patients will be granted access to a graphical representation of exercise history, weight-bearing capabilities of their fracture, and the range of motion in the affected joint. The app will function as a motivational tool for patients, inspiring them to adhere to their workout plans and allowing them to document personal impressions, including pain levels. This data will provide physiotherapists with valuable insights into the patients' at-home exercise regimens. Furthermore, the tool will help sharing important information between healthcare professionals and improve communication between them. Finally, the documentation system will feature a scheduler for physiotherapy sessions, future surgeries, and other appointments, empowering patients to directly arrange appointments with doctors and physiotherapists while receiving timely reminders.

5 STUDY DESIGN

The evaluation of our application will include various studies to be explained later in this section. The aim is to analyse the systems prototype and carry out initial trials in a clinical environment. To examine the subsystems, a technical evaluation will be conducted in a descriptive research design with healthy subjects. For the load measurement system, we need to ensure the validity and reliability of the data. Therefore, we will compare the recordings with a measurement system in the laboratory which we consider to be the gold standard. The same applies to the motion tracking system, where we will compare the results of our single camera approach with MediaPipe or OpenPose with a more complex multi-camera system in the laboratory. Following the technical evaluation, we will continue with a system evaluation including all the single components in a usability research design. Healthy subjects representing patients and healthcare professionals will evaluate the system regarding user-friendliness and patient safety criteria. Once these results have been implemented, initial investigations in a clinical setting are planned. Patients undergoing open reduction and internal fixation of ankle fractures (Weber B type; no syndesmotic rupture) will be recruited. Exclusion criteria would be impaired mobility or gait abnormalities prior to the fracture event, patients with multiple injuries and patients under 18 years of age. Patient reported outcome measures, gait parameters, frequency of use and compliance will be evaluated.

6 CONCLUSION

In conclusion, this paper addresses the pressing challenges within the realm of post-fracture aftercare, recognizing the substantial impact of musculoskeletal injuries on individuals of all age groups and their associated healthcare and socioeconomic costs. The quality of post-injury care is essential in determining recovery outcomes and preventing complications.

Our proposed mobile application, consisting of three core components, presents a promising solution to these challenges. By enabling individualized, self-performed exercise routines, facilitating real-time load measurement, and streamlining data exchange among patients, physicians, and physiotherapists, we aim to enhance the overall quality of post-injury care. The comprehensive methodology outlined in this paper provides a clear path for the implementation of these components, including the innovative use of neural networks for exercise evaluation and the integration of a strain gauge in an implant for load measurement.

In future work, special emphasis should be placed on the continuous refinement of the user interface and user experience. Ensuring an intuitive and user-friendly design will be key to maximising patient and healthcare professional engagement with the mobile application. Additionally we will investigate an approach combining load measurement data with coordinates obtained from pose estimation as inputs for our neural network. This integration has potential to substantially improve the accuracy of exercise assessments, offering a more comprehensive insight into the physical capabilities of patients throughout their rehabilitation process.

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REFERENCES

Braun, B. J., Bushuven, E., Hell, R., Veith, N. T., Buschbaum, J., Holstein, J. H., and Pohlemann, T. (2016). A novel tool for continuous fracture aftercare - clinical feasibility and first results of a new telemetric gait analysis insole. *Injury*, 47(2):490–494.

Braun, B. J., Veith, N. T., Rollmann, M., Orth, M., Fritz, T., Herath, S. C., Holstein, J. H., and Pohlemann, T. (2017). Weight-bearing recommendations after operative fracture treatment—fact or fiction? gait results with and feasibility of a dynamic, continuous pedobarography insole. *Int. Orthop.*, 41(8):1507–1512.

Braun, T., Rieckmann, A., Weber, F., and Grüneberg, C. (2018). Current use of measurement instruments by physiotherapists working in germany: a cross-sectional online survey. *BMC health services research*, 18(1):810.

Bundesagentur für Arbeit (2023). Blickpunkt arbeitsmarkt – fachkräfteengpassanalyse 2022. Technical report, Statistik/Arbeitsmarktberichterstattung, Nürnberg.

Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (2022). Volkswirtschaftliche kosten durch arbeitsunfähigkeit 2021. https://www.baua.de/DE/Themen/Monitoring-Evaluation/Zahlen-Daten-Fakten/pdf/Kosten-2021.pdf.

Cao, Z., Simon, T., Wei, S.-E., and Sheikh, Y. (2017). Real-time multi-person 2d pose estimation using part affinity fields.

Dabke, H. V., Gupta, S. K., Holt, C. A., O'Callaghan, P., and Dent, C. M. (2004). How accurate is partial weightbearing? *Clin. Orthop. Relat. Res.*, 421:282–286.

Fuchs, J., Rabenberg, M., and Scheidt-Nave, C. (2013). Prävalenz ausgewählter muskuloskelettaler erkrankungen. *Bundesgesundheitsblatt - Gesundheitsforschung - Gesundheitsschutz*, 56(5):678–686.

Griefahn, A., Wolf, E., and Zalpour, C. (2020). Wie kann die dokumentation in der physiotherapie durch die digitalisierung effektiver und effizienter werden? – eine delphi-studie. *physioscience*, 16(03):101–110.

Hak, D. J., Fitzpatrick, D., Bishop, J. A., Marsh, J. L., Tilp, S., Schnettler, R., Simpson, H., and Alt, V. (2014). Delayed union and nonunions: Epidemiology, clinical issues, and financial aspects. *Injury*, 45:S3–S7.

Kammerlander, C., Pfeufer, D., Lisitano, L. A., Mehaffey, S., Böcker, W., and Neuerburg, C. (2018). Inability of older adult patients with hip fracture to maintain post-operative weight-bearing restrictions. *J. Bone Joint Surg. Am.*, 100(11):936–941.

Kannus, P., Palvanen, M., Niemi, S., Parkkari, J., and Järvinen, M. (2002). Increasing number and incidence of low-trauma ankle fractures in elderly people: Finnish statistics during 1970-2000 and projections for the future. *Bone*, 31(3):430–433.

Kasnakova, P., Mihaylova, A., Djurdjev, B., and Tornyova, B. (2022). Randomized controlled trial of multidisciplinary rehabilitation therapy using mobile applications in cases of ankle fractures. *European journal of translational myology*, 32(2).

Kassenärztliche Bundesvereinigung KdöR (2022). Regionale verteilung der Ärztinnen und Ärzte in der vertragsärztlichen versorgung. https://gesundheitsdaten.kbv.de/cms/html/16402.php.

Komaris, D.-S., Tarfali, G., O'Flynn, B., and Tedesco, S. (2022). Unsupervised imu-based evaluation of at-home exercise programmes: a feasibility study. *BMC sports science, medicine & rehabilitation*, 14(1):28.

Lara-Palomo, I. C., Gil-Martínez, E., Ramírez-García, J. D., Capel-Alcaraz, A. M., García-López, H., Castro-Sánchez, A. M., and Antequera-Soler, E. (2022). Efficacy of e-health interventions in patients with chronic low-back pain: A systematic review with meta-analysis. *Telemed. J. E. Health.*, 28(12):1734–1752.

Mousavi, S. H., Hijmans, J. M., Moeini, F., Rajabi, R., Ferber, R., van der Worp, H., and Zwerver, J. (2020). Validity and reliability of a smartphone motion analysis app for lower limb kinematics during treadmill running. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine*, 43:27–35.

Reeves, S, P. F. H. R. G. J. and Zwarenstein, M. (2017). Interprofessional collaboration to improve professional practice and healthcare outcomes. *Cochrane Database of Systematic Reviews*, (6).

Rupp, M., Walter, N., Pfeifer, C., Lang, S., Kerschbaum, M., Krutsch, W., Baumann, F., and Alt, V. (2021). The incidence of fractures among the adult population of germany–an analysis from 2009 through 2019. *Dtsch. Arztebl. Int.*, 118(40):665–669.

Teng, K., Eng, C., Hess, C. A., Holt, M. A., Moran, R. T., Sharp, R. R., and Traboulsi, E. I. (2012). Building an innovative model for personalized healthcare. *Cleve Clin J Med*, 79(Suppl 1):S1–9.

Thiengwittayaporn, S., Wattanapreechanon, P., Sakon, P., Peethong, A., Ratisoontorn, N., Charoenphandhu, N., and Charoensiriwath, S. (2023). Development of a mobile application to improve exercise accuracy and quality of life in knee osteoarthritis patients: a randomized controlled trial. *Archives of Orthopaedic and Trauma Surgery*, 143(2):729–738.

Weber, F., Müller, C., Bahns, C., Kopkow, C., Färber, F., Gellert, P., Otte, I., Vollmar, H. C., Brannath, W., Diederich, F., Kloep, S., Rothgang, H., Dieter, V., Krauß, I., Kloek, C., Veenhof, C., Collisi, S., Repschläger, U., Böbinger, H., Grüneberg, C., Thiel, C., and Peschke, D. (2023). Smartphone-assisted training with education for patients with hip and/or knee osteoarthritis (smart-e): study protocol for a multicentre pragmatic randomized controlled trial. *BMC Musculoskeletal Disorders*, 24(1):221.

Weise, H., Zenner, B., Schmiedchen, B., Benning, L., Bulitta, M., Schmitz, D., and Weise, K. (2022). The effect of an app-based home exercise program on self-reported pain intensity in unspecific and degenerative back pain: Pragmatic open-label randomized controlled trial. *J. Med. Internet Res.*, 24(10):e41899.