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Feedback and Analysis System to Improve Partial Weight Bearing and Bone Healing Following Fractures and Osteotomies of the Lower Limb: Technical Note

Zpětná vazba a systém analýzy pro zlepšení částečného zatěžování a kostního hojení po zlomeninách a osteotomiích dolní končetiny: technická poznámka

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ABSTRACT

PURPOSE OF THE STUDY

After the surgical treatment of injuries of the lower extremities or osteotomies, patients are frequently asked to partially load the affected leg during the first weeks of rehabilitation. The patient's compliance to the prescribed weight bearing limit and their ability to regain a physiological gait as soon as possible are necessary for a fast rehabilitation without complications.

MATERIAL AND METHODS/RESULTS

To support patients during this important phase of recovery, we developed a feedback and analysis system that is able to provide feedback concerning loading and roll over behavior to the patient. The system is based on sensor insoles to measure the amount of pressure and pressure distribution and on a smartphone application to provide realtime visual and acoustic feedback.

CONCLUSIONS

This newly developed device has the potential to monitor the rehabilitation phase and assist patients with lower leg injuries therefore decrease the complication rate and enable faster rehabilitation.

Key words: lower limb fracture osteotomy around the knee, partial weight bearing, realtime feedback, smartphone application.

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INTRODUCTION

After injuries or operations of the lower limb, the overall aim is the fast rehabilitation of the patient. This includes the repair of the injured structure as well as the mobility recovery of the patient without complications. For a lower limb fracture or osteotomy around the knee, the primary treatment is the reunion of the bone using an osteosynthesis. Postoperatively, a common rehabilitation method is partial weight bearing (PWB) for several weeks (9, 12). The reduced loading on the affected limb shall protect the osteosynthesis against failure but at the same time it allows an early mobilization of the patient. The mobilization in turn is important for bone growth (5). It has been shown that adequate repetitive loading is necessary to stimulate osteoblast activity and therefore mobilization with moderate load bearing is important for fracture healing (2).

PWB is usually realized with the use of walking aids like forearm crutches. With the help of crutches, load from the lower extremities can be shifted to the upper extremities (hands, arms and shoulders). To perform PWB with forearm crutches in an energy efficient manner, the patients are taught to perform a three-point-gait. This walking style indicates that the affected leg is always with the crutches and therefore the loading on this leg is reduced (8). Because of an alternating walking performance, which can be seen during the three-point walking style, a symmetric gait pattern can be achieved. Thus, the energy costs for walking with crutches are as low as possible although they are still twice compared to normal physiological human gait without walking aids (8). State-of-the-art method to realize PWB using the three-point-gait is that the patients get trained by physical therapists (PTs). The training involves learning about correct weight bearing with a bathroom scale and learning how to perform a physiological gait pattern using the crutches correctly. Weight bearing training

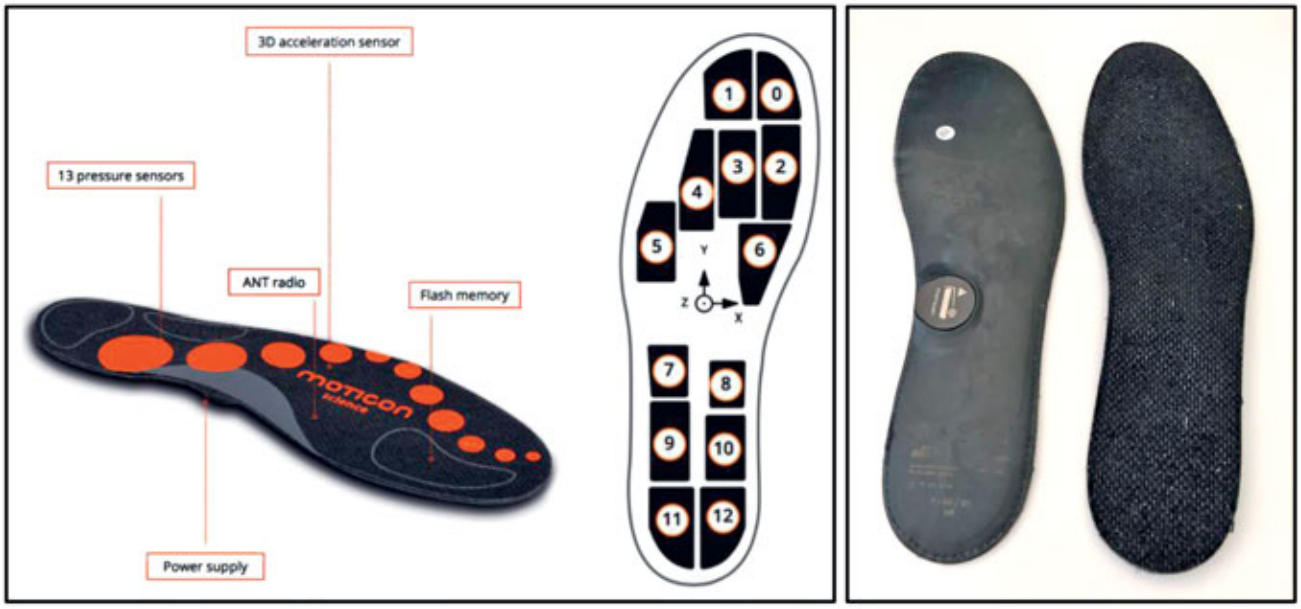

Fig. 1. OpenGo sensor insole system.

happens during static condition. For this purpose, the patient steps on a conventional bathroom scale to get acquainted with a feeling of the prescribed loading. Additionally, to train the correct walking style, the patient receives instructions and feedback from the PT about his/her performance (3, 5, 7). With this method, during dynamic conditions (= walking with crutches) there's no objective feedback about the actual weight bearing for the patient. Therefore it is still unclear how much weight bearing actually happens during walking. Also the evaluation of the walking performance depends on the PT. That means, the evaluation and feedback is subjective and can vary between different PTs. Further, the feedback only happens during therapy session. As soon as the patient has finished the session and leaves the hospital, feedback for weight bearing as well as for walking performance isn't available anymore.

In this background, patient compliance regarding PWB has to be discussed critically. Several studies already dealed with patient compliance during walking with crutches (3, 4, 12). These studies mainly showed poor compliance concerning the amount of loading. Also, there is proof that abnormal gait is common when crutches are used. Li et al. (2001) compared kinetic and kinematic data during three-point crutch walking with normal gait and found significant differences in velocity, cadence, step width and support time for the involved leg (6). Hence, those studies confirm the questionable training conditions.

While some studies suggest that reduced patient compliance and non-supervised PWB and mobilization without restrictions result in slower recovery and more complications (3), Braun et al. (2017) found that there's no correlation between patient compliance concerning PWB and fast recovery without complications (1). All studies did only investigate the amount of weight bearing. Physiological rolling characteristics during walking are not evaluated so far.

Since poor patient compliance regarding load bearing restrictions is a well known problem, big effort has been made to develop feedback systems to give the patients objective and realtime feedback of actual loading (11). So far, no system has been described, that is able to analyze weight bearing and walking style at the same time and provide a combined feedback to the patient.

The working group of this project has now developed a feedback and analysis system to improve PWB and bone healing after fractures or osteotomies of the lower limb. With this system, it is possible to provide realtime feedback concerning actual loading and gait performance to patients with prescribed PWB. At the same time it is possible to monitor and record the performance in and outside the hospital.

MATERIAL AND METHODS/RESULTS

Technique

The newly developed feedback and analysis system consists of a pair of sensor insoles (Fig. 1) to measure plantar pressure and a smartphone application compatible with android, to process the data and provide visual and acoustic realtime feedback to the patient.

OpenGo sensor insole system

To analyze weight bearing and walking performance, we used the validated wireless OpenGo sensor insole system (Moticon GmbH, Munich, Germany) that can be used in any pair of shoes (10, 11). The OpenGo sensor insole system consists of a pair of sensor insoles that hold 13 capacitive pressure sensors each. The sensors can measure the amount of pressure and acceleration (Fig. 1). Through embedded data processing, pressure

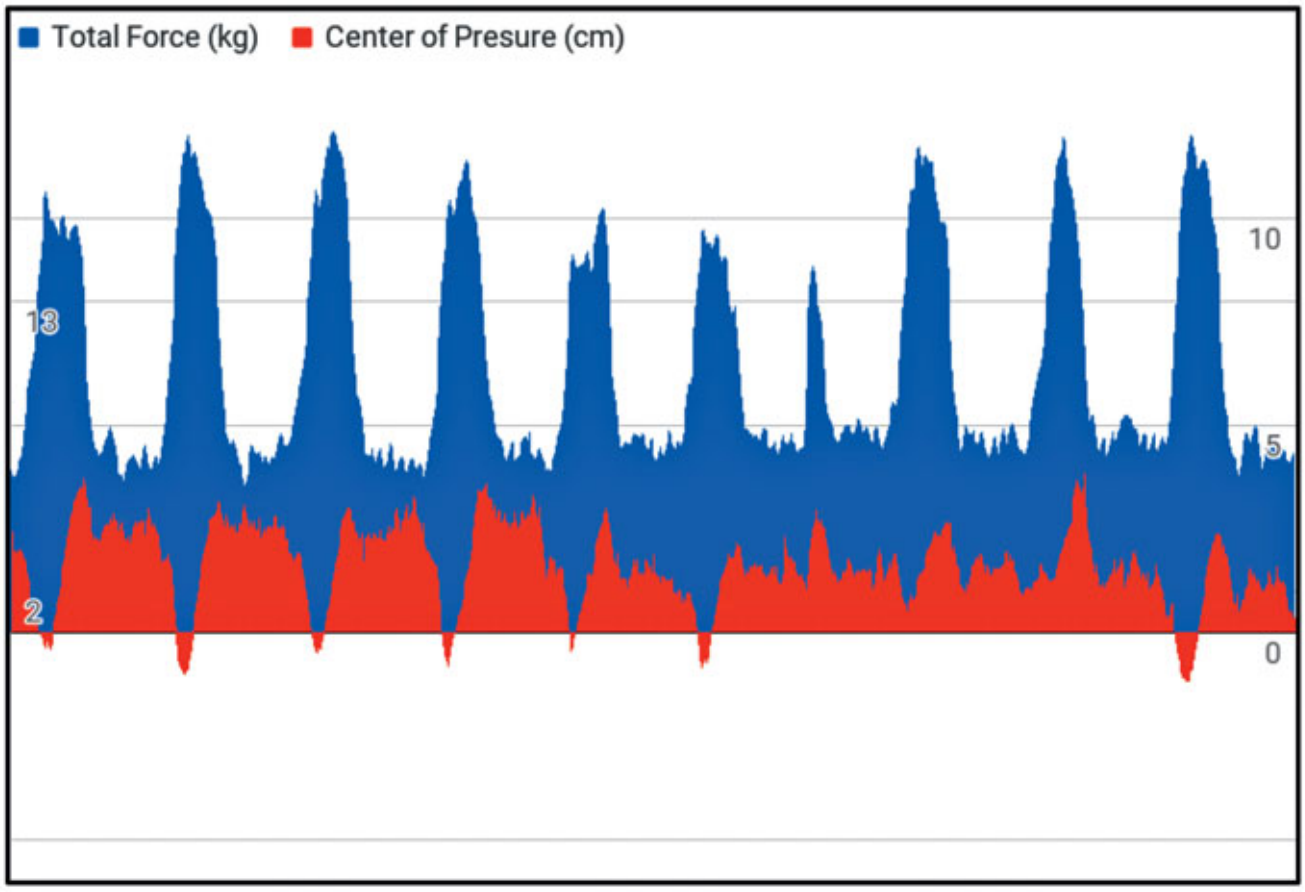

Fig. 2. Total force and center of pressure distribution of the OpenGo sensor insole system of one participant.

distribution and movement can be evaluated and analyzed as well. To ensure the communication between the insoles, wireless data transmission via ANT is possible.

Smartphone application

The purpose of the app is to provide visual and audio realtime feedback to the patient. The feedback is based on two measured parameters: *total pressure* and *center of pressure*. During each step, total pressure value travels from zero (the foot is lifted) to maximal pressure (the other foot is lifted), and back to zero, while the center of pressure changes within a few centimeters, from heel to toes (Fig. 2). The data interface software provided by the insole manufacturer delivers a stream of measurements in form of a tuple, over a generic HTTP interface. For the purpose of portability, however, the data is received locally on the smartphone through a specified port. A low pass filter was applied to handle the noise (especially spikes) in the measurement data, in order to avoid false negative feedback. Since there is a tradeoff between filter efficiency and latency, a moderate filtering was used. Additionally, measurements of less than 4 kg were ignored, as these were mostly caused by the foot pressing against the insole, while the foot is in the air.

The visual feedback on the smartphone screen consists of a gauge, similar to a speed gauge of a common motor vehicle (Fig. 3). The gauge shows the total pressure at the top, and the center of pressure at the bottom. Excessive pressure (pressure over the threshold as entered by the physician) as well as the center of pressure thresholds are shown in red. Acoustic signals were added in order to provide a hand free feedback. During the testing period, student patients preferred to have a continuous feedback, whether positive or negative. Therefore the base sound starts immediately after the foot touches the floor, and stops when lifted. We tested base sound in form of snow crackling under foot, for instance. When the total pressure value exceeds the threshold, as set by the physician, a distinct signal (hitting metal) sounds.

A report is generated based on the past measurements. It shows the total amount of steps, the amount of steps with exceeded pressure, distribution graphs of pressure as well as center of pressure measurements (Fig. 4). The report can be shared through the share functionality of the operating system.

The following conditions were applied in order to detect the beginning and the end of a step. For the beginning of a step: 1) the average of the last 10 measurements of total pressure is higher than the measurement threshold (4 kg) and either: 2) the differential for the center of pressure is positive or 3) the differential of the total pressure measurements is positive (the pressure is increasing). The step ends when the total pressure is lower than

Fig. 3. Display of the new developed feedback and analysis app "BigFoot".

the measurement threshold. In order to avoid a continuous signal when the user rests the foot in the air, we pause the acoustic signal when 1) the differential for the center of pressure is less than 5% of the total step length (the difference between the heel and toes thresholds, as entered by the physician) and 2) the center of pressure did not fall back since the 20 measurements were taken.

DISCUSSION

The presented new feedback system was developed to achieve the primary aim of fast rehabilitation after injuries or osteotomies of the lower limb. This intention shall be achieved through an improvement in patient compliance regarding PWB. A smartphone application was designed to improve patient physiological rolling behavior during walking with prescribed PWB. The app serves as an assistive device to enhance concentration, extend training possibilities and in the end improve learning effects and thus compliance.

The feedback and analysis system has already been tested successfully. For the pretest, physical therapists underwent training sessions with the device. The results show on one hand, that such a system is technically possible and on the other hand it shows that the performance of the users while using the system is promising. Overall higher concentration and positive effects of permanent monitoring and realtime feedback were shown. Regarding the pretest results the possibilities of incorrect PWB performance seem to be considerably decreased. The effect on clinical outcome has to be analyzed in further studies.

The compatibility of the system with state-of-the-art treatment is a major advantage. In detail, the insole system is applicable in any shoe. The new developed App can be downloaded to the patient's smartphone. No wires and besides the insoles, no additional devices are needed. Despite those first positive results, further developments and improvements are necessary. Minor system

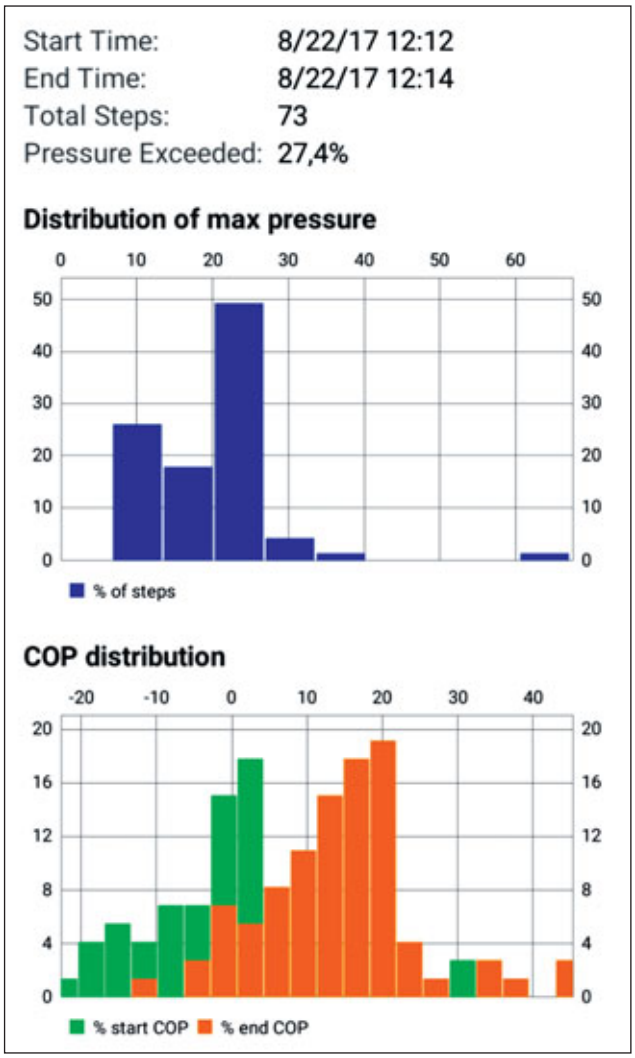

Fig. 4. Gait analysis report of the new feedback and analysis app: distribution of max pressure, center of pressure (COP) distribution.

bugs may impair the physiological gait of the patients. No feedback at all, for example if the loading doesn't exceed the threshold to be count as a step, tends to result in an irregular crutch gait. Furthermore, it was found that the minimal latency of the feedback is essential to whether the patient is going to use it to adjust her loading and gait performance. It was observed that delayed feedback leads to the patient trying involuntary to sync with the acoustic signal and slow down the walk. The combination of feedback (positive, negative, acoustic) has to be evaluated further as well. Possibly, the behavior and acceptance of the system differs between PTs (healthy, mostly physical active people) and patients that underwent an operative treatment after lower limb fractures or osteotomies. For this purpose, further tests with a real patient population using the systems will take place.

Clinical relevance

Over the past years, home rehabilitation systems of all forms became more important. Those systems in general serve as additional and improved treatment options outside the hospital. But at the same time, they also contribute to limit health-related costs. Clinical relevance of the developed feedback and analysis system is on one hand the assistance of patients after injuries or osteotomies of the lower extremities during the rehabilitation phase, and on the other hand, monitoring movement patterns and therefore rehabilitation progress. Monitoring weight bearing and movement compliance of outpatients, can further be used to investigate, and in the end understand, the biomechanics of crutch gait. This in turn could be used to improve treatment methods and to prevent complications occurring during crutch gait and assist in the adoption of efficient gait with the correct use of crutches.

CONCLUSIONS

The presented analysis and feedback system can offer realtime information of weight bearing and walking performance to the patient. The system is easy to handle and provides additional important information to the physician and patient to reduce complication rates and improve rehabilitation protocols following fracture treatment or osteotomies around the knee.

References

1. Braun BJ, Veith NT, Rollmann M, Orth M, Fritz T, Herath SC, Holstein JH, Pohlemann T. Weight-bearing recommendations after operative fracture treatment-fact or fiction? Gait results with and feasibility of a dynamic, continuous pedobarography insole. Int Orthop. 2017;41:1507–1512.
2. Claes L, Wolf S, Augat P. Mechanische Einflüsse auf die Callusheilung. Chirurg. 2000;71:989–994.
3. Dabke HV, Gupta SK, Holt CA, O'Callaghan P, Dent CM. How accurate is partial weightbearing? Clin Orthop Relat Res. 2004;421:282–286.
4. Hurkmans HL, Bussmann JB, Selles RW, Benda E, Stam HJ, Verhaar JA. The difference between actual and prescribed weight bearing of total hip patients with a trochanteric osteotomy: long-term vertical force measurements inside and outside the hospital. Arch Phys Med Rehabil. 2007;88:200–206.
5. Hustedt JW, Blizzard DJ, Baumgaertner MR, Leslie MP, Grauer JN. Current advances in training orthopaedic patients to comply with partial weight-bearing instructions. Yale J Biol Med. 2012;85:119–125.
6. Li S, Armstrong CW, Cipriani D. Three-point gait crutch walking: variability in ground reaction force during weight bearing. Arch Phys Med Rehabil. 2001;82:86–92.
7. Malviya A, Richards J, Jones RK, Udwadia A, Doyle J. Reproducibilty of partial weight bearing. Injury. 2005;36:556–559.
8. Murawa M, Dworak LB, Kabaciński J, Syczewska M, Rzepnicka A. Dynamic parameters of three-point crutch gait in female patients after total hip arthroplasty. Acta Bioeng Biomech. 2016;18:131–135.
9. Schroter S, Ateschrang A, Löwe W, Nakayama H, Stöckle U, Ihle C. Early full weight-bearing versus 6-week partial weight-bearing after open wedge high tibial osteotomy leads to earlier improvement of the clinical results: a prospective, randomised evaluation. Knee Surg Sports Traumatol Arthrosc. 2017;25:325–332.
10. Stoggl T, Martiner A. Validation of Moticon's OpenGo sensor insoles during gait, jumps, balance and cross-country skiing specific imitation movements. J Sports Sci. 2017;35:196–206.
11. van Lieshout R, Pisters MF, Vanwanseele B, de Bie RA, Wouters EJ, Stukstette MJ. Biofeedback in partial weight bearing: usability of two different devices from a patient's and physical therapist's perspective. PLoS One. 2016;11:e0165199.
12. Vasarhelyi A, Baumert T, Fritsch C, Hopfenmüller W, Gradl G, Mittlmeier T. Partial weight bearing after surgery for fractures of the lower extremity--is it achievable? Gait Posture. 2006;23:99–105.

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