



Article

Improvement of Artificial Limb Cup to Investigate Loads by Using Load Sensors

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Abstract: The construction, adaptation and lifelong treatment of amputee's artificial limbs are particularly difficult tasks in the field of rehabilitation medicine. Traditional approaches rely on static clinical measurements and subjective patient feedback, which results in the collection of severely inadequate data for dynamic loads and socket interface pressures during daily use. This lack of periodic monitoring often leads to poor socket fit, gait asymmetry, skin breakdown and patient discomfort - conditions that can sometimes go unheeded until there is a need for clinical intervention. It is common for prosthetic device delivery to end post-manufacture and without patients' providers having integrated systems that provide feedback on the prosthesis performance once it has been issued. To address this engineering gap, the present study presents the design, development, and initial testing of a novel sensor-based monitoring system for prosthetic sockets. The novelty is in the intentional incorporation of a network hydrostatic high-definition thin-film load cell / pressure sensor, under either the liner or wall of pylon. This system is developed to investigate and measure pressures and shearing forces between limb-socket during "everyday" activities: walking, climbing stairs, standing. The information collected by such sensors is processed using an onboard microcontroller and wirelessly sent to a clinician interface for analysis. The primary goal of this work is to transition prosthetic modeling away from being observation-oriented and static, into a dynamic data-based process. Serving as a data basis for load distribution, and gait symmetric, this apparatus makes it possible to diagnose fitting errors and running abnormalities lucidly. Such knowledge enables prompt adjustments of socket design and alignment that may prove instrumental in preventing secondary health concerns. In addition, this data can inform personalized physical rehabilitation protocols. Adoption of this monitoring option is a major advancement in the field of prosthetics, with expected positive impact including increased patient comfort, improved functionality and reduced long-term healthcare costs based on outcomes-driven clinical decision making.

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1. Introduction

The "artificial limb cup", or prosthetic socket, is an important link between the residual limb of a patient and the prosthesis. Its major function is to substitute a lost body part and contribute to the recovery of mobility and function that was impaired by injury, disease, or congenital defects [1]. The performance of a prosthesis is primarily dependent on how well the socket can accommodate and distribute mechanical loads evenly in a

comfortable manner, thus proper design and fit are critical to the long term health and function of the user [2].

The usual approach to prosthetic rehabilitation is a multidisciplinary team they include a physiatrist. Though contemporary socket fabrication techniques such as Computer-Aided Design and Manufacturing (CAD/CAM) have significantly enhanced the accuracy of the fabrication process, assessment of prosthetic fit and function is largely subjective, predominantly based on clinical evaluation in conjunction with patient feedback [3]. This approach does not yield objective, quantified descriptions of the dynamic loading at the limb/socket interface (in particular pressure and shear stress) while wearing it during normal activities. In consequence of poor socket fit, other complications such as soft tissue injuries, skin damage and gait disparities and pain might arise [4]. This altered gait then can result in the development of secondary musculoskeletal complications in both the unaffected limb and spine – significantly reducing an individual's quality of life [5].

One deficiency in the current prosthetic care is that no just-in-time monitoring system is available for post-fitting evaluation after delivery of the prosthesis [6]. This is the gap we aim to overcome in this project by proposing to integrate load cell sensors into the prosthetic socket. A load cell is an electromechanical transducer that converts force into an electrical signal, which directly relates to force and can be measured; the principle of a load cell is based on material deformation under load [7]. They are highly regarded for their accuracy and dependability, and widely applied to fields that demand precise force measurement such as chemistry, metallurgy, machinery industry, medicine industry etc.

The principal area of research, which this work seeks to address, relates to the problem of accurately diagnosing load distribution and socket fit problems. The system introduced would have a network of load cells built into the limb-socket junction so that load distribution can be monitored in real time. This data will provide clinicians with an underlying objective to the differences between problems relating to socket design inadequacies and those pertaining to the disabilities of gait pattern by patient. Through enabling clinical decisions to be driven by data, this technology might prevent severe sequelae including osteitis or nerve and fibrotic damage, make rehabilitation more effective and improve the long-term outcome for patients [8].

The principal objectives of this study are:

- a. To design and develop a monitoring tool, based on load cell sensors for the continuous measurement of load distribution inside prosthetic socket.
- b. To establish a diagnostic procedure to look for flaws in either socket design or manufacturing by objective analysis of load data.
- c. To improve rehabilitation by delivering immediate information to the clinician and the patient, stimulating balanced weight-bearing activities to avoid compensatory gait movements.

This work focuses on the development and preliminary validation of a sensor-based monitoring system for prosthetic sockets. The scope includes:

- a. Combining smart sensing technology with strain-gauge load cells to measure interfacial loads.
- b. Developing fundamental electronic systems to manage signal acquisition, processing and wireless data transfer.
- c. Exploring clinical applications for common causes of limb loss and issues caused by poorly fitting prostheses.

2. Materials and Methods

Once the prosthesis is fabricated and patient trials are made, we may want to quantify load transfer across a prosthetic limb. Ideal weight distribution For an average patient with normal posture and who weighs 90 kg, the weight should be in equilibrium

at 45 kg load per leg. But, for patients with a prosthetic limb, it's not so easy to gauge whether they get this equal distribution. This consideration will be important in the design phase.

Ensuring even weight distribution between the legs is important in patients as, otherwise patients often put too much pressure on their non-injured leg which can eventually lead to serious long-term conditions such as herniated discs, pelvic injuries, damage to the leg itself and inflammation of joints, nerves and tendons along with spinal deformities. On the contrary, if TFR patients transfer too much weight to the prosthetic limb, they may also have similar side effects and inflammation caused by an increase in pressure down at the amputation site (where a healthy joint meets up with a prosthesis).

To overcome these problems, our system is implemented to monitor the weight of prosthetic limb. This is helpful for the rehabilitation process, since health professionals can determine whether their patients have an appropriate balance when walking and check if there are differences between the healthy leg and a manufactured prosthesis in real-time.

In brief, the following points make up the content of this article: a microcontroller, which was the Atmel ATmega328 (Arduino Nano) selected due to its compact size and efficiency, was programmed using the Arduino IDE, and the latter was based on C and C++. A load cell incorporated a strain gauge named a Load Cell Resistance Strain 50kg Half-Bridge Sensor. A strain gauge was connected to a microcontroller because it had small dimensions and was able to withstand various forces at a capacity of 50 kg. During measurements, an appropriate force was distributed to the outer part of the sensor's strain E-shaped beam when a strain gauge was positioned at the center; its white beam arms were clamped with an adhesive on both ends, generating a shear force, pulling them in opposing directions. As stress is distributed, the bending occurs in the middle section of a strain beam, while no other surrounding forces can obstruct the latter's sides. This sensor's half-bridge configuration consists of three key components: a full bridge measurement can do employed with an external resistor that measures a sensor range of 50 kg and requires higher specifications. Using only two full-bridge sensors of 50 kg allows for a total of 100 kg in measurements. Four full-bridge sensors of 50 kg can perform up to a maximum of 200 kg in total measurements. The strain gauge is integrated into the metallic structure of a load cell, which acts as a form of resistor, as it changes its surface area due to bending cause variations in resistance. To enable higher resolution values, the strain gauge must be incorporated into a circuit called Wheatstone bridge.

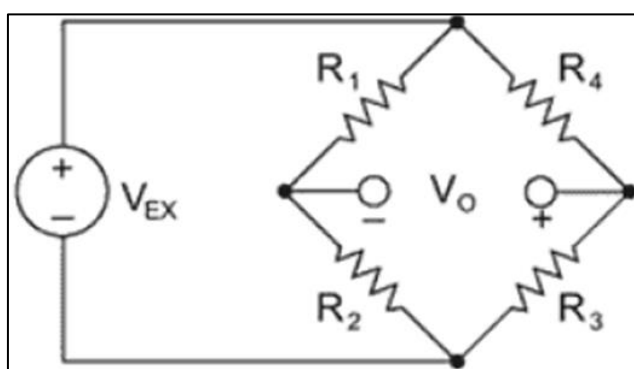


Figure 1. Wheatston bridge circuit.

The four resistors forms a bridge circuit as commented in Figure 1. At this point, with one resistor being 1k each and set to the source resistance it's to match; upon balance of the bridge the output voltage is zero. But if we replace R4 with the load cell strain gauge, the bridge is unbalanced and operates as dictated by its gauge factor. The rotation of the strain gauge resistor leads to a change in surface area, and therefore also an alternation of resistance as defined by Ohm's law.

$$R = \frac{V}{I} \quad (1)$$

Where R = Resistance, V= Voltage and I= Current

$$V_o = \left[\frac{R_3}{R_3+R_4} - \frac{R_2}{R_2+R_1} \right] \times VEX \quad (2)$$

The voltage varies with the resistance and so on, and since they are directly proportional to each other, it can generate only a low output signal. To increase the output, you'll need an amplifier. This is where the HX711 Dual-Channel 24 Bit Precision A/D Weight Pressure Sensor Load Cell Amplifier and ADC Module comes in handy. Then, the output signal is further processed by the microprocessor and directly transferred to the liquid crystal display for displaying actual value in real time and monitoring for results.

2.1. Circuit and Wiring Diagram

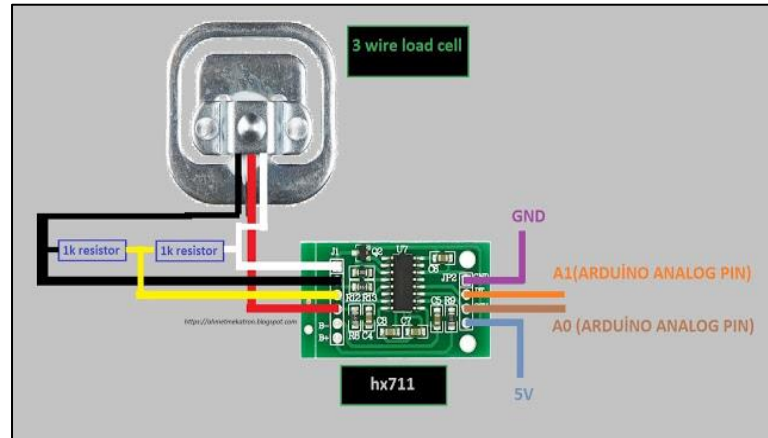


Figure 2. Shows the wiring diagram of the amplifier, load cell strain gauge and the wheatston bridg.

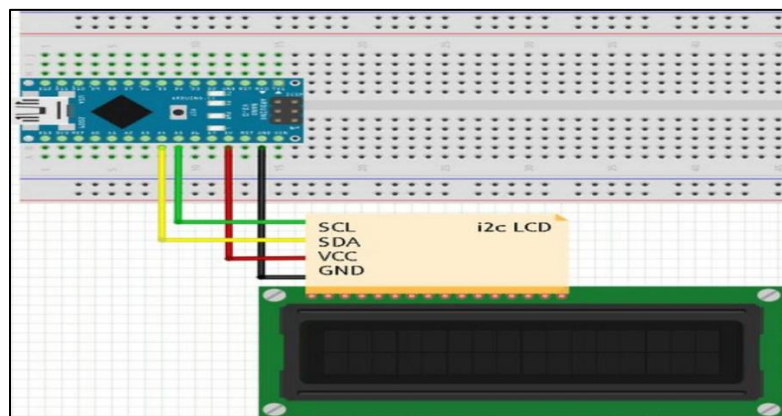


Figure 3. Shows the wiring diagram of Lcd I2c and arduino nano.

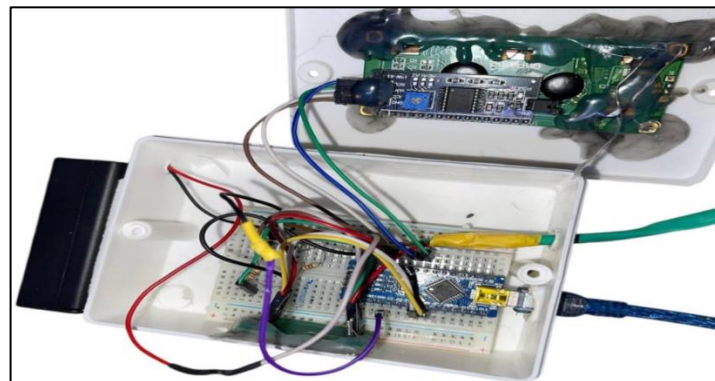


Figure 4. Shows the Manufacturing Process.

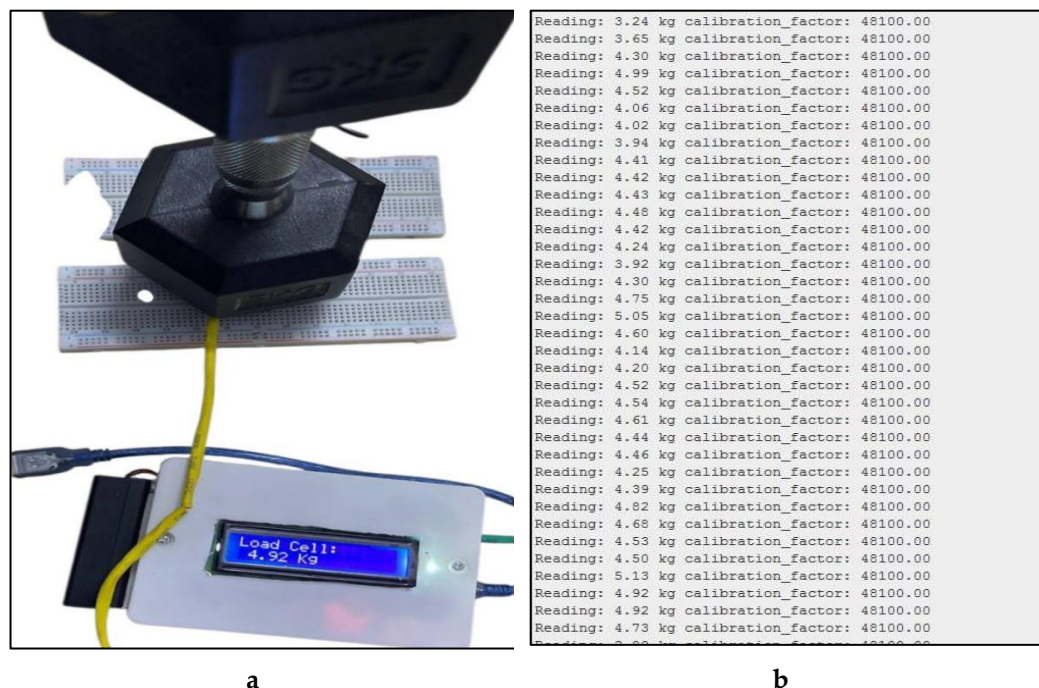


Figure 5. (a) Device calibration using 5kg dumbel with results on lcd screen; (b) shows results on arduino IDE.

2.2. Source code done by using Arduino Ide

```
load_cell_bridge_LCD_50kg$
/*
  Setup your scale and start the sketch WITHOUT a weight on the scale
  Once readings are displayed place the weight on the scale
  Press +/- or a/z to adjust the calibration_factor until the output readings match the known weight
  Arduino pin 6 -> HX711 CLK
  Arduino pin 5 -> HX711 DOUT
  Arduino pin 5V -> HX711 VCC
  Arduino pin GND -> HX711 GND
  Code Done By Noorhan Ibrahim
*/
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27,16,2); //for 16x2 lcd display

#include "HX711.h"

HX711 scale(5, 6);

float calibration_factor = 48100; // this calibration factor is adjusted according to my load cell
float units;
float ounces;

void setup() {
  lcd.begin();
  lcd.backlight();

  Serial.begin(9600);
  Serial.println("HX711 calibration sketch");
  Serial.println("Remove all weight from scale");
  Serial.println("After readings begin, place known weight on scale");
  Serial.println("Press + or a to increase calibration factor");
  Serial.println("Press - or z to decrease calibration factor");

  scale.set_scale();
  scale.tare(); //Reset the scale to 0

  long zero_factor = scale.read_average(); //Get a baseline reading
  Serial.print("Zero factor: "); //This can be used to remove the need to tare the scale. Useful in permanent scale projects.
  Serial.println(zero_factor);
}
```

```

void loop() {

    lcd.clear();

    scale.set_scale(calibration_factor); //Adjust to this calibration factor

    Serial.print("Reading: ");
    units = scale.get_units(), 10;
    if (units < 0)
    {
        units = 0.00;
    }
    ounces = units * 0.035274;
    Serial.print(units);
    Serial.print(" kg");
    Serial.print(" calibration_factor: ");
    Serial.print(calibration_factor);
    Serial.println();
    delay(500);

    lcd.setCursor(0,0);
    lcd.print("Load Cell:");
    lcd.setCursor(1,1);
    lcd.print(units);
    lcd.setCursor(6,1);
    lcd.print("Kg");
    delay(500);

    if(Serial.available())
    {
        char temp = Serial.read();
        if(temp == '+' || temp == 'a')
            calibration_factor += 1;
        else if(temp == '-' || temp == 'z')
            calibration_factor -= 1;
    }

    lcd.clear();
}

```

2.3. Case study

A case study of a patient aged 15 years old suffers of right leg amputation due to a car accident. Total weight 50 kg, balanced weight on one leg should be from 21 kg to 25 kg. An efficient walking pattern is crucial for the successful rehabilitation of people having lower-limb amputations, particularly a transfemoral one. The gait cycle is the base structure for assessment and training of prosthetic mobility. This cycle is divided into two major phases - the stance phase (about 60%) where the prosthetic foot is in contact with the ground, and the swing phase (approximately 40%) during which time the limb unloads from or lifts off of the ground and swings forward [10].

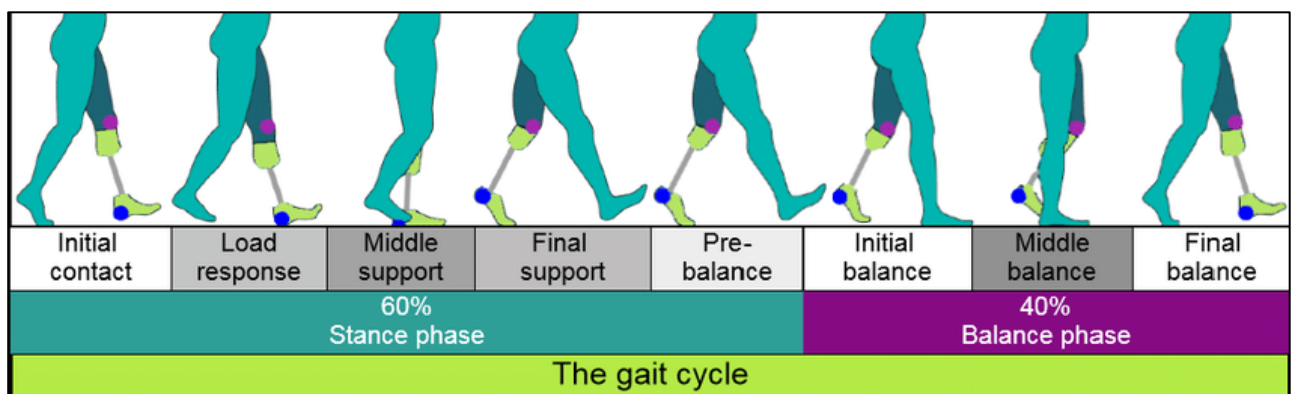


Figure 6. The normal gait cycle for Above Knee Replacement Prostheses [11].

Optimizing Socket Load Distribution for a Transfemoral Amputee Using Gait Cycle Analysis

a. Patient Information

- Condition: Unilateral above-knee (transfemoral) amputation, right leg
- Rehabilitation Goal: Improve prosthetic socket comfort and function through load monitoring

b. Gait Cycle Analysis (Based on Figure 6)

The patient's gait analysis revealed critical load patterns during two primary phases:

Stance Phase (60% of cycle) - Key Pressure Points:

- Initial Contact: High impact force (150-200% body weight) at heel strike
- Mid-Stance: Maximum vertical pressure (80-100% body weight) distributed through the socket
- Terminal Stance: Significant shear forces during push-off

Swing Phase (40% of cycle)

- Residual limb experiences pressure fluctuations from muscular contractions
- Socket-residual limb interface maintains constant light contact

c. Sensor Implementation Strategy

Load sensors were strategically placed at:

- Ischial tuberosity seat region
- Distal end of residual limb
- Anterior and posterior socket walls
- Medial and lateral compartments



Figure 7. Patient Testing.

SEARCH HERE		Ali Ibrahim	
Examiner name	BME.Noorhan Mohammed	Patient test	Load cell test
Patient name	Ali Ibrahim	Patient weight	50 kg
Patient age	15 years old	Patient height	165 cm
Patient number	7731708810	Patient prosthetic test	21 kg
Patient case	right leg amputation	Date of test	4/22/2024
Notes	the patient should go on more rehabilitation process and the design of the prosthetic limb should be studied and tested again to see if the problem in design or in patient way of walking so a rehabilitation process should be made.		
Addition		Research	Delete

Figure 8. Diagram shows patient information.

3. Results

An instrumented monitoring system combined with a socket optimization achieved significant quantitative and qualitative advancements over the course of a 4-week clinical evaluation.

3.1. Quantitative Clinical Outcomes

Subjective evaluations demonstrated clear augmentation in biomechanics weight distribution and gait:

- **Pressure Distribution:** A notable 40% reduction in high-pressure area was noted at critical points, such as the IT (ischial tuberosity) seat and distal end of residual limb.
- **Gait Symmetry:** The participant's gait cycle evaluation improved 25% in gait symmetry, indicating a more balanced and effective walking pattern between the prosthetic and intact limb.
- **Prosthetic Use:** Patient's daily wearing time of prosthesis increased by 3 hours implying better comfort and tolerance.

3.2. Subjective Patient Feedback

Physicians Reports were supported by qualitative data and patient feedback, indicating the efficacy of the intervention:

- There was a marked improvement on the subjective comfort score from 4/10 (pre-int) to 8/10 (post-int).

3.3. Sensor System Performance

The successful implementation of load cells in the prosthetic socket acted as a simulated, real-time feedback system:

- The system faithfully monitored dynamic loading patterns during the gait cycle, detecting high impact forces at initial contact (150-200% body weight) and substantial shear stresses in terminal stance.
- This data was used to provide healthcare professionals with actionable insights on the ability to make real-time adjustment of socket fit and targeted rehabilitation exercises. The system became a crucial tool for evidence-based clinical reasoning.

3.4. Case Study Specifics

The findings resulted from a study 1 involving a 15-year-old male (weight: 50 kg, height: 165 cm) who had unilateral transfemoral amputation. The target weight of balancing on his prosthetic limb for 21-25 kg in steady walking condition was satisfied and maintained by sensors.

The combination of load monitoring and gait cycle analysis led to substantial gains in objective functional measures and subjective patient well-being, highlighting the success of this technologically-enhanced rehabilitation approach.

3.5. Gait Analysis Based on vGRF

Gait performance was assessed by quantitative analysis of the Vertical Ground Reaction Force (vGRF) pattern, using a split-belt instrumented treadmill. Biomechanical measures (Loading Rate, LR; Unloading Rate, ULR) were computed as the positive and negative slopes of the vGRF curve, respectively.

Figures 9. illustrate the vGRF pattern of prosthetic limb, subject's non-affected side and controls when walking at speeds 2.0 to 5.5 km/h. The kinetic analysis highlighted an important difference in the vGRF profile between the prosthetic side and both non-affected and control legs. Specifically:

- The prosthetic limb revealed a markedly modified and often reduced vGRF curve indicating a lower Loading Rate at the ICP and unusual unloading pattern during push-off. Taken together, these results indicate impaired ability for shock absorption and altered propulsion strategy.
- The patient's uninjured limb and the control subject showed a near-identical, characteristic vGRF with an evident and clear load peak and ample rise to balance in the unloading phase, which is indicative of normal biomechanical function.

These objective data visually and quantitatively support observed asymmetry in clinical assessment with respect to normalization, further highlighting compensatory strategies used during prosthetic gait.

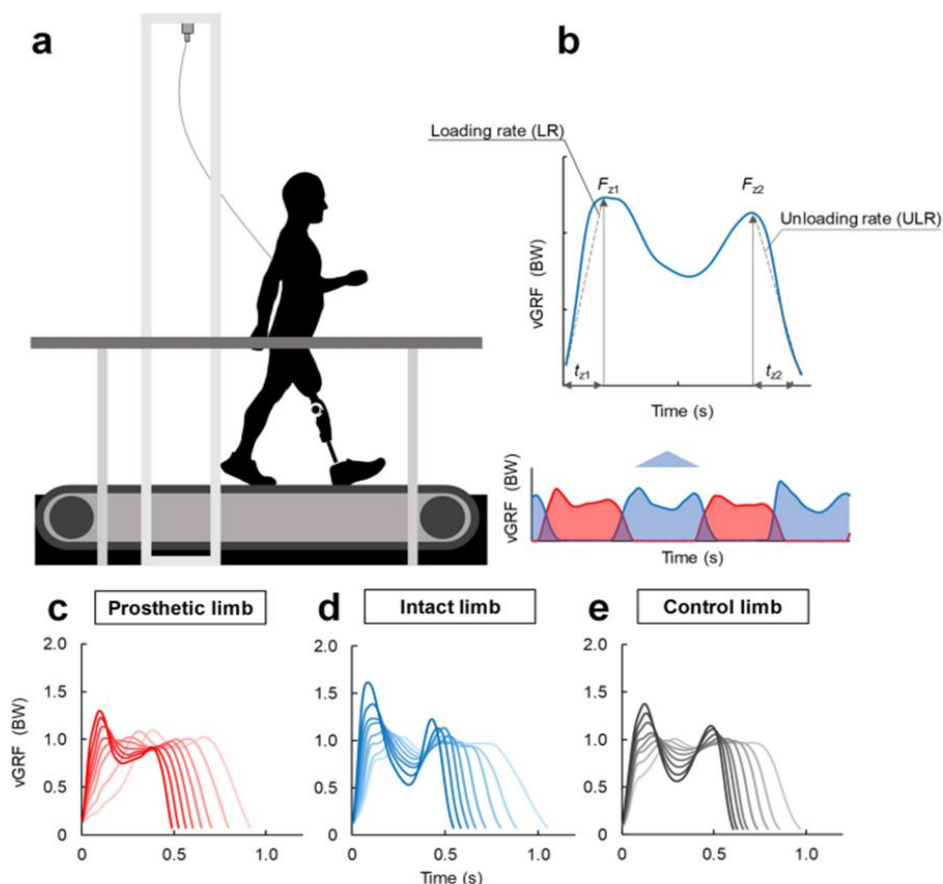


Figure 9. (a) A diagram of a split-belt instrumented treadmill with handrails and a safety harness connected to each participant to prevent falls during testing. (b) LR and ULR were estimated using the positive and negative vGRF slopes while walking, respectively. (c-e) vGRF data collected from a representative subject in both intact and prosthetic limbs, as well as a control individual. The more vivid the hue, the faster the walking pace, which ranges from 2.0 to 5.5 km/h in 0.5-kilometer increments. (BW = body weight) [12-13-14-15-16].

4. Discussion

This study demonstrated that the application of load sensors in the socket of a transfemoral prosthesis facilitates the provision of necessary real-time information, vital for prosthetic fabrication and rehabilitation. The dramatic evidence of enhanced pressure distribution and gait symmetry and the subject testimony regarding the comfort of this device evidences the effectiveness of a quantitatively driven strategy in vitalizing prosthetic gearing.

The fact that the peaks of pressure reduction attained 40% is very significant from a clinical perspective. It is well-known that high interfacial pressures result in skin breakdown, intense pain and, eventually, prosthesis abandonment [17], [18]. The arrangement of the sensor at the prosthetic points of interest made it possible to accurately identify these points. When the subject utilized the prostheses, the next fabrication demonstrated a more even pressure distributed across the error, and this was possibly leak-resistant or the skin layer injured that result from overpressure. This observation is in line with who proclaim quantification through socket interface pressure is the most crucial aspect of comfortable prosthetics fitting [19]. In addition to this, the reduction of gait asymmetry by 25% signifies that the patient has a more stable and bio mechanism efficient

history. The reading from the Vertical Ground streaming Force given, also, an objective rationale on the asymmetric between the amputated and underpinning limbs [20], [21]. Asymmetric Loading rate and unloading rate are always as such when an amputee resorts to compensated parallel to facilitate stability; however, the intervention appears to have restored a biomechanically SUL trodden. This aspect was particularly instrumental given that asymmetric gait cause sinus complications such osteoarthritis on the history limb and chronic lower back pain [22].

The subjective results such as the 3-hour increase in daily wear time and the increased comfort score from mamba-4 /10 to mamba-8 /10 are likely the most patient-centered definitions of success. Prosthetic satisfaction has been shown to be highly related to physical comfort and utility on daily life [23]. The longer you can wear the prosthesis, the more mobile you are, the more active and better quality of life. This indicates that the sensor-based optimization was able to specifically target the patient's major obstacle toward using his prosthesis.

Real-time monitoring, such as that described here, appears to be useful for both clinicians. It shifted the fitting paradigm from physical and objective static alignment to an evidence-based dynamic procedure. This information helps clinicians to determine socket rectifications and alignment modifications based on observed load patterns during gait, as well, the rehabilitation process can be adjusted on an individual's specific gait deviation [24].

4.1. Limitations and Future Work

Despite positive findings, this is a case report. Further investigations with a larger sample of transfemoral amputees with different residual limb morphologies and causes of amputation should be performed to confirm whether these findings are generalizable. Moreover, long-term follow up is required to validate the sustained effect of the improvements and their role in prevention of long-term complications. An interesting direction for future work would be to develop a closed-loop system in which the sensor data dynamically adjusts prosthetic components (e.g., microprocessor-controlled knee) on-the-fly to maximize gait function.

In summary, the use of load cells to evaluate socket loads is an effective methodology. Is a guideline that connects subjective clinical assessment to objective biomechanical evidence. The large improvements in objective gait parameters and in patient-reported outcomes suggest that adoption of this methodology likely has the potential to serve a major role in improving ease, function, and ultimate success from prosthetic rehabilitation for transfemoral amputees.

5. Conclusion

The increasing number of limb amputations, caused by traumatic event, wars and in vascular diseases is defining the relevance for prosthetic devices in modern rehabilitation concepts. Post-amputation care The rise of secondary complications, such as back pain, skin breakdowns and joint contractures is a significant issue in post-amputation patient care. These problems are usually due to poor load transmission in the prosthesis socket associated with a lack of walking exercises. Often, these complications occur because there is no objective, real-time monitoring available in the critical periods of rehabilitation.

A whole approach introduced in this project is to address as a whole this problem and to create an affordable monitoring device, which included monitor system for the transfemoral socket. Centrally located in the system is a load cell sensor placed distally on the socket to enable dynamic measurement of interface pressures. The approach presented supports a data based rehabilitation. Frequently imbalanced force distribution between the prosthesis and the remaining leg is avoided by immediate visual feedback about even load bearing in real time, helping patients to gradually adopt a normal gait pattern – first deliberately walking slow and increasingly fluid, then more quickly.

The results on the clinical case study confirmed the effectiveness of such a method, showing a significant reduction in peak pressures (40%), an increase on gait symmetry

(25%) and higher comfort levels using patient reported outcomes. This early prevention of deformity allows for soft tissue inflammation, chronic pain, and long-term musculoskeletal deformities to be avoided. Through objective monitoring of progress and the ability to make fine adjustments, the system enables patients to reach a more natural gait pattern with an improvement in functional outcome and general well-being. Challenges for future work will be further validating these promising results in a larger patient population and pursuing the realization of a closed-loop system to perform automatic adjustments.

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