Real-time interfacial load monitoring and tracking between the composite prosthetic socket and residual limb for below-knee amputees.

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Abstract

Real time-in-service interfacial load measurement and load tracking between prosthetic socket and the residual limb is of paramount importance. Noroozi et al proposed an inverse method approach using ANN to predict the magnitude and location of the interfacial load between prosthetic socket and the residual limb from the structural response of the socket to the normal internal load due to contact between the stump and the socket. Here the socket mechanical properties act as the transfer function between the forces acting normal to the internal surface of the socket forces and the resultant strains generated on the external surface of the socket. Using this method, it is possible to use the external strains to predict the internal load that caused the strain. With this method, there will be no need for the socket or tissue properties or the exact socket thickness. Using this technique, one can simply transform everyone's socket into their own dedicated transducer suitable for measuring, tracking and monitoring the resultant interfacial load on the internal surfaces of the socket for that user. Currently, all socket interfacial load measurement systems require tactile sensors which require the prior knowledge of the location of the contact points. This makes it impossible for the tactile sensor to predict the magnitude and location of high-pressure points. Alternative tools are tactile sensor placed in liners or drilled and mounted through the socket wall, or total surface bearing ones that are subjective and not suitable for everyday use. For that reason, they require the knowledge of the contact point or areas of high load intensities. The proposed new system requires none of the above constraints and due to its unique design, it is immune to the changes in the overall boundary conditions, making it an invaluable clinical system.

1. Introduction

Sensor Technology Development for use in the Biomedical and BioMechanical application is primarily concerned with the rapid development of a tool to sense measure, assess and communicate vital Biomedical and biomechanical parameters for the masses. Continuous remote health and condition monitoring technology is well placed to have an impact in preventive medicine. Wearable Electronic sensors can play a vital role within this field. This is very fortuitous as the rapid development and research into the manufacturing and utilisation of these sensors have seen an exponential rise in the last thirty years. This paired with fasters more powerful CPUs and software capable of running complicated algorithms and pre and post signal processing makes the notion of real-time health monitoring a reality.

It is interesting to compare the how these milestones have influenced the wider implementations of condition monitoring into more and more complex applications with varying degrees of autonomy and intelligence. Ultimately is there a limit to what the technology can offer or the development curve never ending.

The interfacial pressure between an amputee's residual limb and the prosthetic socket is an important clinical issue in the prosthetic fitting process due to the problems associated with poorly fitted sockets. A Real-time Artificial Neural Network (ANN) and experimental datasets have been combined and developed a Hybrid real-time load measurement and tracking system that can predict the magnitude and location of the centre of pressure between regions of the prosthetic socket and the matching regions on the residual limb.

In real life, these pressures must be distributed such that the gait is stable and energy-efficient. Good mechanical coupling is needed between the prosthetic socket and the residual limb to allow the amputee to walk comfortably and for an extended period of time. The existing experimental measurement techniques(1;2;3;4;5;6)always interfere with the data obtained because transducers are either placed between the skin and socket or positioned within the socket wall. Therefore the sensor always changes the interactions at the interface or the socket geometry. Clinical uses of such sensors are therefore limited to research activities only and are not used to aid the prosthetist in determining the fit of a prosthetic socket. The main limitation is that measurement is restricted to the points directly under the sensors. Increasing the number of sensors will make the patient's movement even more difficult, limiting mobility and affecting dynamic measurements(4)Finite Element Analysis (FEA) (7;8;9;5;10;11;12) has also been applied extensively but with limited success. The lack of success is usually due to limitations and/or simplifying assumptions in the model such as inadequate implementation of constitutive laws for tissue properties (overall tissue properties are difficult to model and constitutive laws are case dependent and only apply to specific tissues such as skin, bone or muscle), non-uniform wall thickness of the socket, geometrical modelling difficulties, realistic boundary conditions and loading modelling problems(13)and Composite properties. Replacing experimental data with FEA data for training the ANN is only possible for well-defined linear elastic homogenous structures with a simple mechanical load which is not the case in a prosthetic socket and a Residual limb scenario. A more practical, less invasive and passive sensing approach is needed to overcome some of the problems identified by(14)and thus aid prosthetic fitting techniques. The focus of this paper is to propose a tool for a day-to-day application within the clinical environment. The hybrid semi-inverse approach is defined as the application of combined experimental and Artificial Neural Network (ANN) methods. The theory behind this approach has been discussed in detail elsewhere(15;16) and an overview of the approach is summarised below.

ANN methods represent an engineering discipline concerned with non-programmed adaptive information processing systems that develop associations (transforms or mappings) between objects in response to their environment. That is, they learn from examples. ANNs are based on brain-like information encoding and processing models and as such, they can exhibit brain-like behaviours such as learning, association, categorisation, generalisation, feature extraction and optimisation.

An ANN can often be thought of as black box devices for information processing that accepts inputs and produces outputs (Figure 1). In this study, an ANN function in Matlab was adopted for this application. It used surface strains to predict the interfacial pressures at the residual limb/socket interface. To achieve this ANN requires a number of example input and output data for training (i.e. relating the network inputs to outputs using a transfer function and series of weighting values). New surface strain data can then be introduced to the trained ANN (problem data) to give the predicted pressures.

The low-cost sensor that does not require modification of the socket geometry is the Electrical Resistance Strain Gauges (ERSGs). The systems proposed by Amali and Sewell can suffer from inaccuracies due to variable boundary conditions during both the training and the socket assessment. These errors cannot readily be corrected or rectified both in training and during measurements due to issues associated with both materials and geometrical nonlinearity as well as dynamic or sometimes random nature of the boundary condition. To avoid or minimize the effects of changes in the boundary conditions and materials and geometrical nonlinearities the number of sensors used to determine and track the magnitude or position of the single moving load over a given surface patch only 3 RESG were used for each of the 3 main surfaces of the socket. The 3 ERSGs are located at 3 extreme location on each patch of the surface as seen in fig-1. The socket is then modified such that all the force/load paths from any single normal internal load on the patch must go through the 3 ERSG isolating the patch from the rest of the structure, making the system unique and immune to the changes of boundary conditions such as non-linear displacements or materials.

By limiting the number and position of the sensors to 3 per large surface patch we can eliminate any mechanical crosstalk and any effect due to variation in the boundary condition of the socket. With 3 transducers one can practically measure and locate any point load anywhere on the surface of the patch. The resolution and accuracy will be the function of the requirements and is left to the discretion of the AI trainer.

To detect, track and quantify the location and magnitude of the overall load or the centre of the pressure inside the socket the whole surface of the socket is divided into 3 large surfaces. Each surface is linked to the rest of the socket using 3 tabs where the ERSG are located on. A single Microcontroller is capable of simultaneously powering and measuring sensor that together covers the entire surface of the socket. Total Force each of the 3 patches can now be measure located and monitored in order to inform clinicians or the user or activation of joint control units in real time and independently Figure 1 shows the schematic diagram of the electronic system designed to run the system.

At the Heart of the system, there is an Arduino Microcontroller called Arduino nano. This is in turn connected to 4 programmable amplifiers. Using this technique there will be no need to have the prior knowledge of the position of the maximum load within the socket. Whereas with conventional transducer studies a sensor must be placed at each intended location and is limited to a single value and not optimum. Potentially applying this technique to the actual socket can predict the pressure at many locations with a minimal number of sensors, improving patient mobility thus allowing full dynamic assessment.

This paper presents results of a laboratory trial utilizing the technique mentioned above to determine its potential as a clinical tool used to translate the internal surface pressure into a single resultant force acting at a point. By reducing the number of sensors required for a large patch, (unlike Amali & Sewell,) to only 3 per patch we overcome the sources of inaccuracies such as material properties Thickness and variable boundary conditions.

The aim here is to provoke fellow researchers into exploring alternative techniques for solving this complex problem which so far has not been successfully achieved by using transducers or FEA alone.

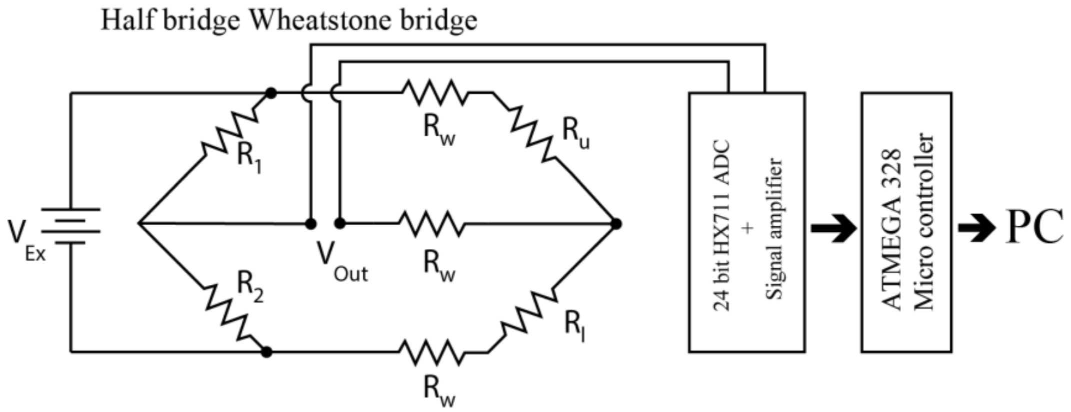


Figure 1. Illustrates a Half bridge Wheatstone configuration, the ADC and the ATMEGA processor.

2. Methodology and test procedure

The method for developing a system to predict the pressure at the residual limb/socket interface is discussed in detail in the following sections and is summarised in steps listed below:

1. Collect experimental data to validate experimental data :
    a) Divide the internal surface of the socket into 3 large regions.
    b) Provide each region with 3 stress resistors and place an ERSG at each stress raiser.
    c) 1 ERSG is then attached on the outside surface of the socket and on every stress raiser.
    d) Use markers and map a Grid on the surface of each region. It must be noted that the resolution of these grids depends on the user and can be a coarse or as fine as possible. Number these grid points according to your own convention.
    e) Attach the sensors to the programmable amplifiers and then to the Arduino microcontroller.
    f) Connect the Arduino to a laptop that contains MATLAB and Arduino programming environment.
    g) Run the code and wait for it to initialise.
    h) Apply a known load to a pint on the grid and collect readings from the 3 ERSG that are directly connected to the 3 stress raisers for that region/patch.
    i) Repeat this process for every point on the grid and store them in Excel as the first training or checking data.
    j) Assuming linear elastic property of the socket material and geometry we use a random number generator to create a large amount of training data needed for training the ANN.
    k) Use some of the collected data for the check to see if absolute minimum or convergence has occurred.
    l) Train the network, as usual, using the data generated above and wait for it to converge.
    m) Develop a compensatory ANN to reduce the error in the FEA model by training the ANN using experimental results as the output and FEA results as the input.
    n) Once the system is trained the weights are transferred and stored on Arduino for real-time prediction.

   o) To test the system, an unknown load is then applied at a grid point and system detects its magnitude and location.
   p) This load is then moved around and the tracking and force can be tracked in real time as it can be seen on. (Insert a link)

2. Validate the HIPE (Hybrid Inverse Problem Engine) through two studies to compare the predicted pressures on the inside of the socket with actually applied pressures.
3. Use the HIPE to predict the level and position of the pressures inside the surface of the region inside the volunteer’s socket.

3. Circuit Design

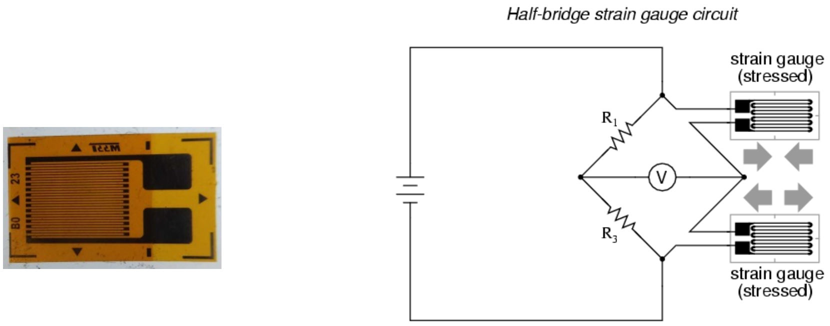
Three 320Ω foil strain gauges, which are originally variable resistance affected by stretching Figure 2 (a), are mounted precisely on regions with a high strain in direction of X as illustrated in Figure 3. Generally, strain gauges connection can be formed in full bridge, half bridge and quarter Bridge. In this design, each strain gauge forms a half Wheatstone bridge configuration using one temperature compensator strain gauge and two external resistors and powered with regulated 3.5V DC. As shown in Figure 2 (b), the two strain gauge is used to overcome the temperature effect where one of the gauges is mounted under load changes and the other isn’t affected by load. In this case, the temperature change effect will be counted during measured voltage calculation in the processor according to the following equations obtained from [17]:

$$R_G = R_{G0} + \Delta R_\theta + \Delta R_\epsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (1)$$

Where

$R_G: guage\ resistance$
$R_{G0}: nominal\ resistnace$
$\Delta R_\theta: Temperture\ change\ effect$
$\Delta R_\epsilon\ change\ of\ resistance\ due\ to\ the\ strain$

The bridges are then connected to an ATMEGA 328 microcontroller through a high-resolution ADC (24 bit HX711) with the gain of 128. The signal amplifier is used because the produced voltage is few millivolts while the microcontroller measure and process signals up to 5 V as illustrated in Figure 1



(a) (b)

Figure 2. (a) Strain gauge, and (b) half-bridge strain gauge configuration.

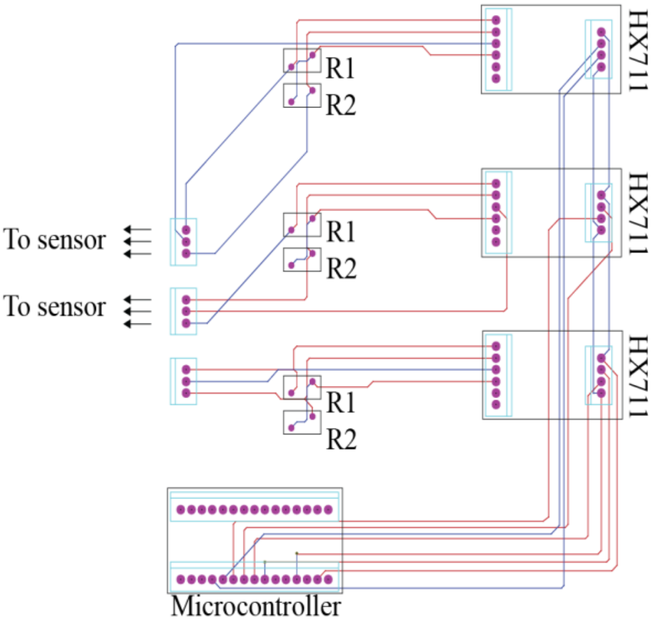
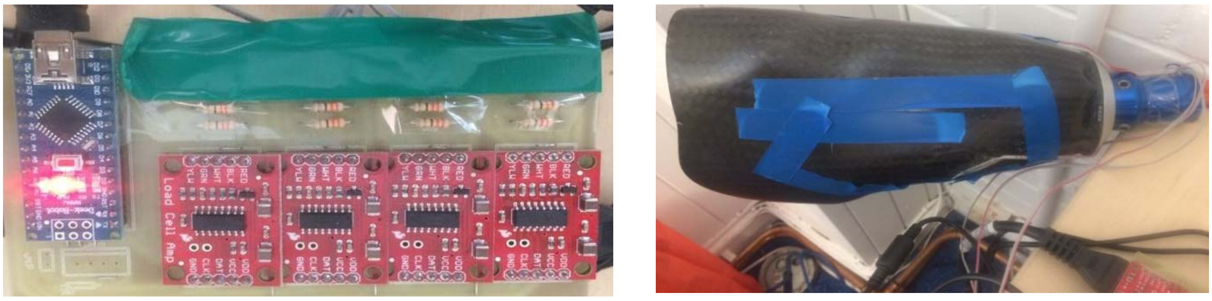


Figure 3. The configuration of many sensing points connecting with the same controller.



(a)

Figure 4. Illustrates the practical implementation of the circuit (a) and attaching the stain gauge in (b).

(b)

4. Experiments and results Discussion.

A simple C shape loading mechanism was improvised to apply a constant load to the inside surface of the socket as seen in Figure 5 The key point being the load is always normal and there are no shear forces as the contact point is exactly above the applied load. A video clip showing the system is in (18).

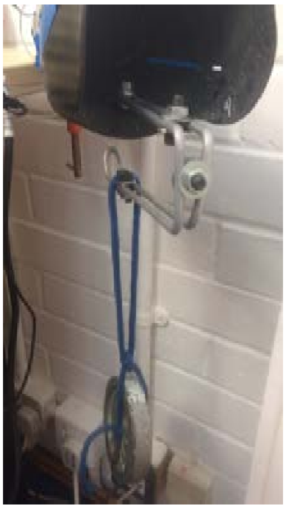
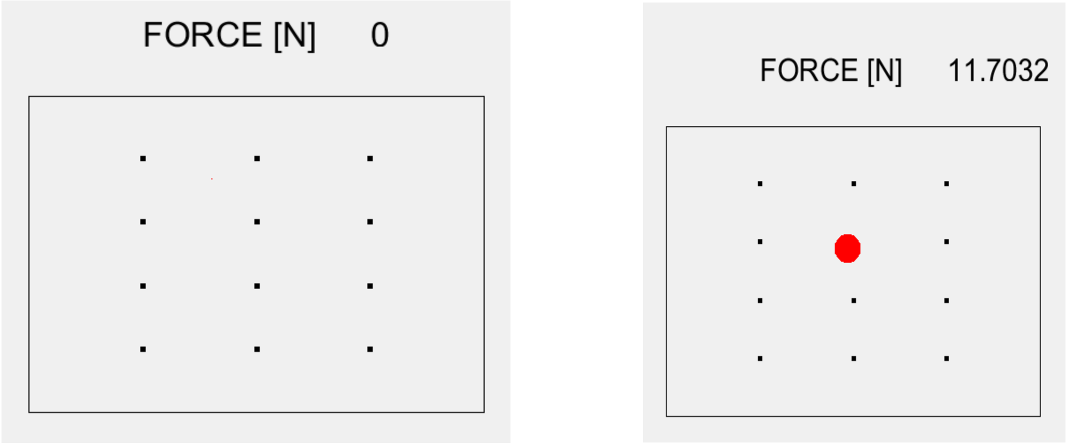


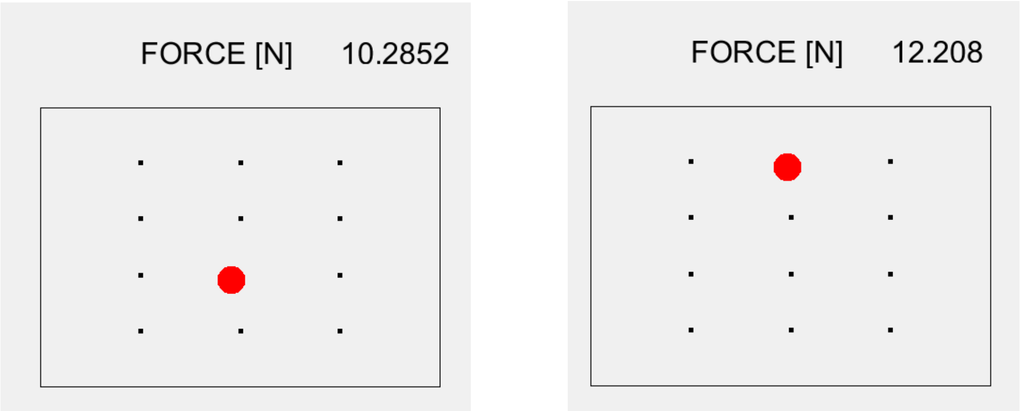
Figure 5. The improvised loading hook.

Figure 6(a,b,c,d) show the various state of the Graphical User Interface (GUI) of the system showing both the Gridpoint where the load is acting is being detected. Also the value of the applied load that is acting on the socket at that grid point. For a better appreciation of the performance of the socket load tracking system Please use the link below.

It must be noted that this experiment was devised quickly just to show the power of the Real-Time Hybrid Inverse Problem Engine (HIPE) system using ANN. Higher resolution, better accuracy, can all be improved by training it using substantially more random noisy data. In this format, it can be a used for clinical and gait analysis applications where socket and intelligent knees can work together to achieve better and smoother function.



(a) (b)



(c) (d)

Figure 6 showing load being predicted at various point on the inner surface of the socket.

As it can be seen from the Youtube clip and the above the real-time in-service socket interfacial load tracking and measurement system clearly works and in this state requires no prior knowledge of instrumentation, electronics, programming, FEA or composite. All is required is basic knowledge of load transfer and effect of load on an elastic structure. The transducer used here is ERSG but it does not have to be. Any other forms of transducers that can provide a voltage proportional to a random remote load will be enough. Other issues that resulted in some inaccuracy and drift was that lack of thermal compensation. The ERSG were a ¼ bridge formation and prone to thermal drift. In a future design, the half bridge is proposed with one gauge acting as a thermal compensator. Reusable ERSG can be used but permanent one will make everyone's socket into a real-time transducer dedicated to that person and the system can be used on a daily basis using a battery pack or Mobile phone for storage and communication of the data.

5. Conclusion

Socket interfacial pressure measurement has been the subject of research by many researchers and has been investigated for well over 30 years. Until now non-viable solutions have been offered that can actually measure the correct contact force and its location between the socket and the stump. FEA based systems are not practical as tissue or composite properties are subjective and non-linear. The socket has its own issues such as variable thickness and anisotropy which makes them difficult to model in FEA or analyse due to unknown shear and poisons values through the thickness. Using tactile sensors can be accurate but knowledge of the contact location is a must and can not be predicted and sensor placement in socket disturbs the flow of force. Measurement of strains and shear in liners is the current trend but again it deals with the diffused load and difficult to the differential between shear and normal force as they both emit a similar signal.

Photo stress in practice five a full picture of shear stresses over the entire socket. The contours of Princiap stress or strain differences are the exact measures of od the shear stress or strains in the wall which are the consequence of sump socket interaction.

That brings us to the conclusion that our proposed system appears to be the only solution in this field and this contribution here make it an invaluable tool as it is immune to changing of boundary condition, Dissimilar or unknown material properties. Lack of adequate knowledge of the magnitude or location of the load location. It's transformation between walking and running and its intensity and rate of change etc.

Being able to monitor the interfacial load between socket and the residual limb in real time has never been materialised until now and this is the first transducer of its kind that removes the subjective and the artisan fashion socket fit has been passed software and make it more deterministic and objective with quantifiable results that can be repeated or used as reference to detect changes.

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