DYNAMOMETRY AS A MEAN TO NON-INVASIVELY ESTIMATE CARDIAC OUTPUT

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Abstract: The present work deals with the feasibility of a system that can extract BKG through platform dynamometry and thus estimate the cardiac output through reverse modelling. 10 subjects underwent quiet stance trials with simultaneous recording of ECG signals. Cardiac activity force, and the estimation of the cardiac output were extracted through averaging and reverse modelling. Estimated values for cardiac parameters are consistent with the regression with anthropometrical factors, such as body surface area, and confirm the feasibility of a non invasive technique based on dynamometry to provide information on cardiac function.

Introduction

Instrumented force platforms have been extensively used to analyse human movement when associated with different tasks in the framework of Rehabilitation, Sport Activities, and Human Performance: load transducers, either strain-gauged or piezoelectric, make it possible to obtain information on the 3D Ground Reaction Force vector (GRF) acting upon the Centre of Mass (CoM) when subjects are asked to execute movements such as Gait, Step Negotiation, Sit to Stand.

Endogenous sources of mechanical *stimuli*, such as haemodynamics, ventilation, and peristalsis, determine extremely tiny variations of the GRF, and can thus be sensed only by extremely sensitive and accurate transducers: moreover, the forces exerted in the execution of motor activities by far exceed in amplitude the endogenous forces, and thus completely conceal their effect.

Conversely, when the subject is asked to maintain stillness, either in stance or when sitting, the variations of the reaction force with respect to gravity are relatively small, and some evidences of both haemodynamics and ventilation have been isolated in quiet upright stance trials [1, 2, 3]. In particular, by coherent averaging the three components of the GRF vector with ECG recordings as trigger, the ballistocardiographic (BCG) effect on the 3D force vector in upright stance has been identified in peak to peak values around 2 N on the vertical component and 0.5 N in the anterior-posterior direction, whereas the medial-lateral direction does not appear as dependent on the ejection of blood [4], and by restricting the analysis to the sagittal plane, the effect that this internal source of perturbation determines on the body oscillations has been estimated in around ± 0.3 mm in anterior-posterior direction [5]. Thus, platform dynamometry can tested as a tool to extract information on the mechanical effect generated by the heart , i.e. Ballistocardiography.

Though conventional Ballistocardiography has been historically projected as a non invasive tool to estimate cardiac function, the encumbrance of the instrumentation for the execution of the trials prevent the technique from being widespread as a clinical tool. The overall instrumentation generally consists of a table suspended from the ceiling on wires, braced to prevent motion in any but the longitudinal direction, and able to record the movement of the bed due to the recoil of the human body within each heart beat [6]. Other techniques have been proposed more recently to record the mechanical effect of blood ejection in aorta in systole, thus including the static-charge-sensitive bed (SCSB) [7], and the electromechanical film (EMFi) [8].

Independently from the recording techniques, the analysis of BCG signal historically followed a deterministic approach, in that the objective was to identify the physiological cause that generates each pulse wave of the BCG, in the same manner of the ECG signal. This approach, though apparently thorough from a clinical perspective, has some limitations coming from the uncertainty of the estimation caused by the transmission of the pulse wave through the body. The presence of fat, skin, and muscles makes the assumption of the human plant as a simple attenuator far from reality.

As a result, the classical estimation of cardiac output from BKG signal suffered from dependence on diverse biomechanical variables, as the result of height, weight and body constitution, and thus failed in providing accurate results, if compared with other obtrusive methods, such as thermo-dilution.

The novel approach proposed in this work makes use of a system identification approach by combining platform dynamometry for the extraction of BCG signals with an interpretative model that estimates cardiac output as the input of a black box model, whose features can be obtained by multivariate fitting.

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Materials and Methods

A home-made strain gauged force platform has been specifically developed in the laboratory to obtain a high sensitivity in the determination of the vertical component of the ground reaction force vector (7.12 mV/N with external amplification), yet granting a sufficient bandwidth (resonance frequency over 75 Hz).

Figure 1: The Force Platform.

Table 1: Font Sizes and Styles

Subject	Height	Weight	BSA	BMI
S1	1.63	49.05	1.49	18.5
S2	1.58	46.85	1.43	18.8
S3	1.63	52.20	1.53	19.6
S4	1.64	56.18	1.59	20.9
S5	1.64	56.76	1.60	21.1
S6	1.68	61.76	1.69	21.9
S7	1.61	60.36	1.64	23.3
S8	1.77	64.68	1.78	20.6
S9	1.81	69.89	1.87	21.3
S10	1.79	72.60	1.90	22.7

A sample population of ten healthy young volunteers (aged 23-25) with no regress cardiovascular or neuromuscular reported pathologies consented to participate in the study.

Information on anthropometric values is reported in Table 1. Body Mass Index was calculated according to the formula $BMI=M/H^2$, whereas Body Surface Area BSA was estimated according to the Mosteller's regression formula [9].

They were asked to stand quietly on the force platform placed upon their feet, breathe normally, and maintain that position for 90 s.

The test was repeated three times, and between repetitions a rest interval of three minutes was consented.

Electrical signals coming from the force platform were amplified, filtered, and fed to a high resolution A/D converter with a conservative value for the sampling rate of 2000 samples/s for the sampling rate, thus allowing a finer temporal resolution for the BCG signal.

Force plate signals were recorded simultaneously with ECG data (II lead), as extracted from a multichannel acquisition device (StepPC, by Demitalia s.a.s.) that served as trigger for the synchronous averaging.

For every trial and for each condition, the vertical component of the ground reaction force was thus divided into different segments, starting from the time instance when the R peak of the QRS complex on the ECG signal occurred. Thus, by coherent averaging of the signal segments, an estimate of the force signals correlated with the cardiac activity was determined in the two different conditions, $R_1(t)$ and $R_2(t)$, respectively. For each trial, the number of epochs ranged from 85 to 112, thus allowing for a decrease in the variance of the uncorrelated signal of about an order of magnitude.

Once the vectors were isolated, one parameter was directly extracted from experimental data, corresponding to the standard deviation of the averaged signals, σ_R. Then, the experimental signals were considered as the outputs coming from the same input, denoted as $A_{max}f_c(t)$ with $\max\{f_c(t)\}=1$, but passing through second order mechanical systems characterized by a set of different biomechanical factors, i.e. stiffness values k_z and damping coefficients, b_z, as represented in Figure 1.

The first assumption for the time history of the cardiac source, as generating at the aorta level, was a simple pulse, thus obtaining a bivariate set of pulse responses, as a function of the Vertical Stiffness, k_z, and the Vertical Damping, b_z: the values of k_z and b_z were estimated by fitting the normalized pulse responses with the experimental data recorded at the foot floor interaction. Since about one order of magnitude divides the vertical component of the ground reaction force from the non vertical components, and the transverse excitation could not rotate the axis of the plant of more than about 0.1°, the plant axis can be replaced with the vertical one, and the vertical component can be considered as the response of the whole pulse at the aorta level.

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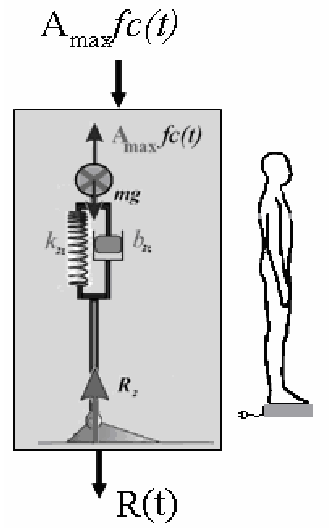

Figure 2: Layout of the modelling scheme.

The value of the maximal amplitude A_{max} was then re-determined by utilizing the estimated values for the viscous-elastic parameters, thus obtaining an index for the Cardiac Output.

Results

Experimental data directly coming from the force platform allowed the extraction of the vertical component of the cardiac activity related force vector, which resulted repeatable among trials for every subject, and with moderate subject specificity.

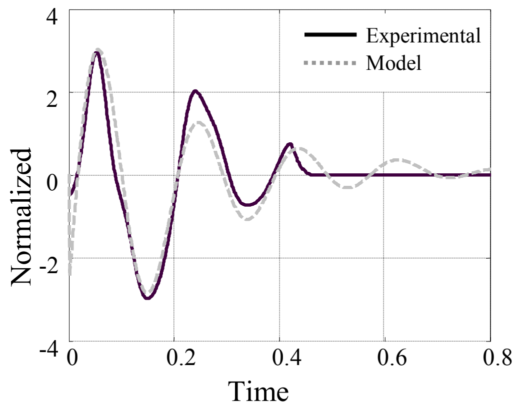

Figure 2: experimental Data for a stance trial on subject S3 (black line), and fitted model data with Bz=##, and Kz=##.

Modelled results show an estimate of k_z in the range 74.7 ± 6.2 kN/m, b_z 509.2 ± 66.5 Ns/m (Mean population value ± Interindividual Standard Deviation). The stiffness values showed low inter-trial variability, and moderate inter-individual variability. No significant correlation was however found with anthropometrical factors for k_z.

Damping values showed low intertribal variability, and moderate inter-individual variability. As expected, b_z correlated with BMI ($R^2 > 0.6$).

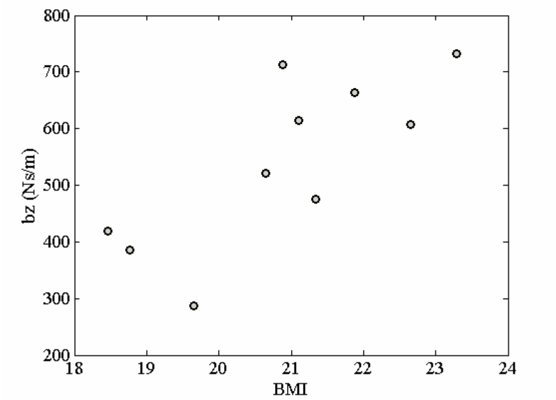

Figure 3: Scatter plot of modelled A_{max}, with respect to the body surface area standing position.

The modelled values for A_{max} were found in the range (2.2 – 4.7 N), and these values can be considered as consistent with the force exerted with the ejection of blood in aorta.
Moderate correlation was found with height ($R^2 > 0.72$), with weight ($R^2 > 0.9$), and even higher with BSA ($R^2 > 0.92$), and this finding is in accordance with the hypotheses of a strong relation between cardiac output and body surface area [9]. Similar considerations, even if with lower values for the correlation with anthropometrical factors, apply for σ_R.

Table 1: Estimated and Experimental Data

Subject	**A_{max} (N)**	**σ_R**
S1	2.52	0.79
S2	2.30	0.73
S3	2.53	0.80
S4	3.03	0.95
S5	2.55	0.80
S6	3.66	1.15
S7	3.43	1.08
S8	3.81	1.20
S9	4.11	1.29
S10	4.72	1.48

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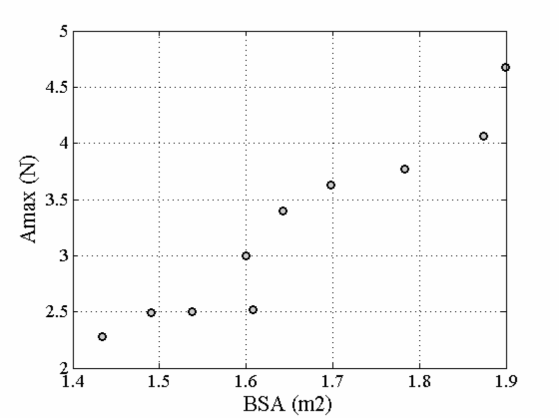

Figure 3: Scatter plot of modelled A_{max}, with respect to the body surface area standing position.

Discussion

The present work confirms that monitoring cardiac function can thus be done by the use of a force plate under the feet of the patient, that can stand directly on the force plate: the technique can be made even more robust if the subject sits on an instrumented chair, because in this second condition the effect that body sway determines on the amplitude of the force vector is by far reduced.
Moreover, the estimation of A_{max} as an index for cardiac output seems promising, as it is consistent with the hypothesis of the force exerted by the stroke volume when ejected in aorta.

Conclusions

Preliminary results are encouraging, and open new *scenarios* in the assessment of cardiac function in a non intrusive environment. Following this perspective, the authors suggest the development of an instrumented armchair to be used at home in telemonitoring programs. Future developments will regard the fine tuning of the technique for the averaging, with the possibility of self-triggering for the heart beat, in view of an even simpler and even less invasive and encumbering method for the quantification of cardiac activity force.

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