Leg-specific Separation of Running Vertical Ground Reaction Force Signals

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***Abstract*— In this paper, we propose guidelines and techniques for optimally handling Vertical Ground Reaction Force (VGRF) signals acquired during running. For that endeavor, we developed an algorithm that performs leg-specific signal separation in an adaptive manner such that each VGRF signal is decomposed into two equally-sized time series each being specific to one of the two legs. Our technique was applied on single-channel VGRF signals recorded via instrumented treadmill during a 24-hour marathon performed by 12 athletes. The purpose of proposing such techniques lies in the fact that the VGRF signal carries combined data relevant to both legs' anatomical and physiological states and its analysis may only describe overall running characteristics, neglecting the importance of inter-leg symmetry in rehabilitation and performance analysis which requires leg-specific analysis.**

I. Introduction

Vertical Ground Reaction Forces (VGRF) have been studied for decades in various domains such as walking and running biomechanics [1], athletics [2] and rehabilitation [3]. The acquisition of VGRF signals has been performed using a variety of techniques, the sensors being attached to the subject's foot as a shoe-sensor array [4] or exterior to the subject such as the treadmill ergometer or instrumented treadmill used in the present study [5]. The first acquisition scheme offers a more realistic approach through which the subject is not bounded in a laboratory-like facility, which proved to be useful in case the purpose of the study is to model the effect of terrain variability upon the subject's walk or run [6]. On the other hand, the treadmill ergometer acquisition scheme offers an engineered and tailored environment that allows the scientists to have control over the different variables such as speed, terrain and distraction level for more accurate and reproducible results in VGRF modeling [7] and fatigue assessment [8].

However, the vast majority of published literature deals with VGRF signals as double-legged signals in which repetitive strides are sequentially captured. Consequently, any analysis technique whether in the time domain or the frequency domain will lead to a general conclusion regardless of the inter-leg micro and macro-differences.

A major metric in the abovementioned fields is the inter-leg symmetry, which carries anatomical and physiological information that is indispensable for limb recovery in case of rehabilitation and athletic performance tracking in the sports field [9]. One may interject and say that there is no need for the separation into two single-sided time series for the analyst to be able to assess inter-leg symmetry, and we agree. However, the proposed method majorly facilitates the analysis and classification phases when performed as pre-analysis method.

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II. Materials and Methods

A. Database Description

In our research, we acquired the VGRF of fourteen male volunteers (mean _ SD: age 41.1 ± 8.9 years; weight 73.6 ± 8.2 kg, height 176.9 ± 5.8 cm, body mass index (BMI) 23.5 ± 1.9 kg/m^2 and body fat: 17.7 ± 4.3%). They were recruited among experienced ultra-endurance runners and all of them had run at least a race longer than 24 h or 4100 km. On average, they had 15.3 ± 7.1 years of training history in running and 7.1 ± 4.4 years of ultra-endurance experience. They reported to run an average of 80.5 ± 11.7 km/week. Written informed consent was obtained from the subjects. The study was conducted according to the Declaration of Helsinki. The protocol has been approved by the local ethics committee (Comité de Protection des Personnes Sud-Est 1, France) and registered in http:// clinicaltrial.gov (# NCT 00428779). Among the 14 subjects, 12 were able to complete the 24TR. One subject was excluded by the physician because of a hematoma due to the initial muscle biopsy procedure and the other one was excluded because of low blood pressure.

Each subject was asked to run for a duration of 20 seconds every 2 hours for 24 consecutive hours, and the VGRF of the 20-second runs (12 recordings for each of the 12 subjects) were recorded and saved. The acquisition of the desired VGRF signal was performed using 4 force sensors located in the corners of an instrumented treadmill described as shown in Fig.1.

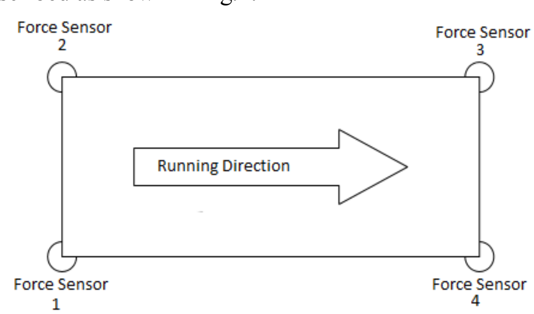

Figure 1. Instrumented Treadmill VGRF Sensor Localization.

B. Single-Channel VGRF Signal

When a subject walks on a platform, whether on the ground or on a treadmill, a downward and backward force vector is produced and exerted by the walker, which is opposed by an equal and opposite force, i.e. upward and forward force, which is the force measured via force plate.

This Ground Reaction Force may be broken down into the three dimensions that are termed in biomechanics: Vertical, Horizontal and Medio-lateral Ground Reaction Force [10]. The force of interest in our work is the Vertical GRF known as VGRF, which is chosen for analysis by the vast majority of researchers for its well-defined pattern and relatively-high amplitude.

The VGRF signal is defined a sequence of double-peaked step-signals, each couple of which is termed stride, being the right-foot step and the left-foot step. The double-peak pattern is in fact the manifestation of the heel-strike, during which the foot is in contact with the ground, followed by the toe-off, during which the toes are pressing on the ground to push the body forward. That being stated, it is expected to have a force signal, during running, that has serially-defined couples of peaks, the first peak being lower in amplitude and sharper than the second body-pushing peak; these two peaks are termed Impact Peak and Propulsive Peak, respectively [11]. The abovementioned pattern description is shown in Fig. 2 in which a series of four steps during a running activity is shown.

Regarding the processing of the VGRF signal, the details of which are outside the scope of this paper, a smoothening operation has to be performed over the signal in order to flatten the baseline along with the peaks, which may be performed via low-pass filtering. The smoothing filter chosen in the presented work is a 4^{th} order Butterworth filter, which leads to acceptable baseline flattening and peak smoothening without any remarkable loss of Impact Peak definition, as shown in Fig. 3.

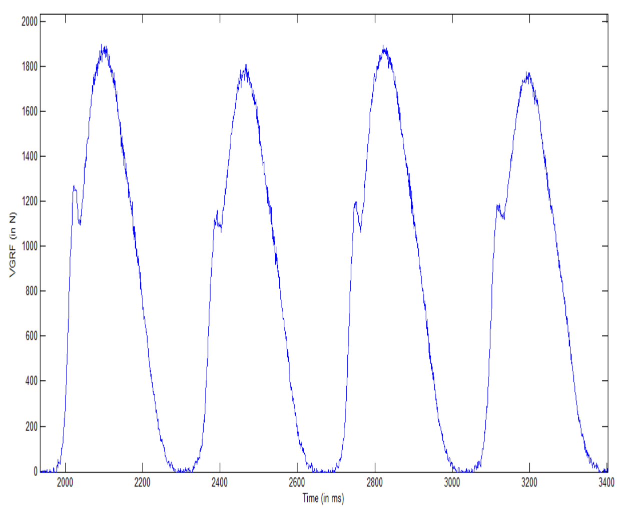

Figure 2. 4-step Running VGRF Sample Signal.

C. *Leg-Specific Signal Separation*

As already mentioned throughout this paper, the single-channel VGRF signal carries left leg and right leg information, which are to be separated if thorough and leg-specific analysis is to be performed. Similarly to any algorithm, a set of constraints is pre-existing and must not interfere with the designed functions.

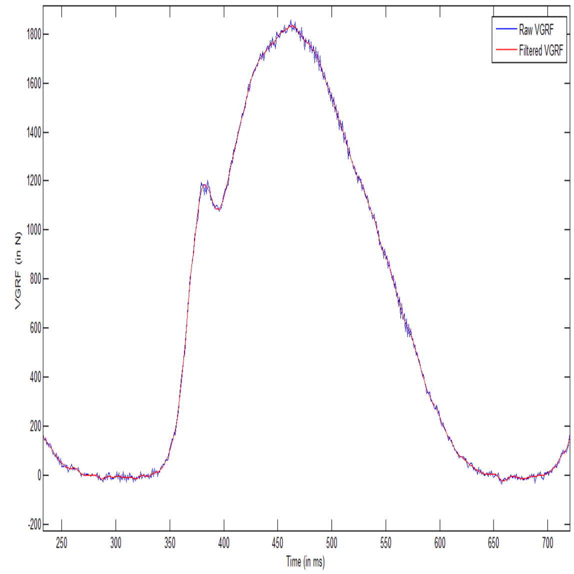

Figure 3. Raw vs Filtered Single-step VGRF.

In our case, the speed of the runner is not constant in function of time, taking into consideration the inter-runner capability of maintaining constant performance and definitely taking into consideration the onset of fatigue and how the runner handles it. This creates a constraint which is the lack of predictable timing between steps and strides, preventing us from segmenting the time-series into equally sized step- or stride-fragments, hence the need for adaptive segmentation.

As solution to the stated constraint, we figured we would detect the Propulsive Peaks, out of which a minimum threshold is set; whenever the filtered VGRF signal crosses the threshold, which is set to 5% of the smallest Propulsive Peak, one of two flags is set or reset depending on the threshold crossing direction: if the threshold is crossed by a rising force signal the rising-edge flag is set, and if the threshold is crossed by a falling force signal the falling-edge flag is set. Once the flags are saved along with their setting/resetting times, the step-limiting instants are computed as the midpoints of the segments joining the falling and rising edges, as shown in Fig. 4.

Now that the step edges are detected, their time indexes are saved and the midpoints are computed, an alternating selection of steps is performed such that one step out of two is chosen and the successive step is zero-padded; a step is defined in this paper as the signal in between midpoints. In order to simplify the explanation further, the algorithm is presented as follows:

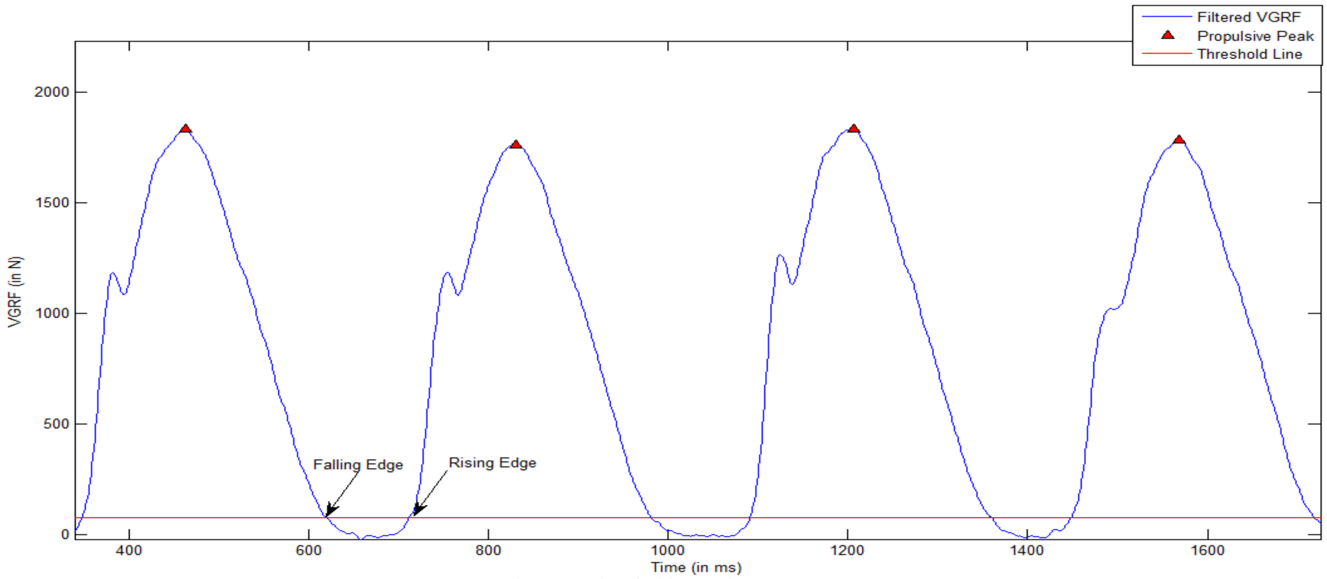

Figure 4. Threshold Crossing Instants.

Algorithm: Left-Right Leg VGRF Isolation

Input: **(**1 x *N*)-vector **VGRF**

Output: Two (1 x *N*)-vectors: **leg1_VGRF** and **leg2_VGRF**

Procedure:

1. Filter **VGRF** using a smoothing 4th order Butterworth low pass filter;
2. Find the propulsive peaks after setting minimum peak height and minimum peak distance;
3. Set a 5% **threshold** of the smallest peak;
4. Compute the difference between **filtered_VGRF** and **threshold**;
5. Set **leading_edge_found** flag to 0;
6. Set **j** to 0 and **k** to 2;
7. Initialize **leg1_VGRF=VGRF**;
8. Initialize **leg2_VGRF** = **VGRF**;
9. **for** i ← 1 to (*N*-1) **do**

    repeat

    if (leading_edge_found = 0 *and* difference(i)<0 *and* **difference(i+1)>0)**

    leading_edge_found=1;

    j=**j**+1;

    step_edges(j)=i;

    end

    if (**leading_edge_found** = 1 *and* **difference(i)>0** *and* **difference(i+1)<0)**

    leading_edge_found=0;

    j=**j**+1;

    step_edges(j)=i;

    end
10. Locate the midpoints between respective falling and rising **step_edges;**
11. Adjust **leg1_VGRF** by zero-padding it between **step_edges** in a step-alternating fashion;
12. Set **leg2_VGRF = VGRF – leg1_VGRF;**

Note that the legs were assigned the names *leg1* and *leg2* simply because the analyst may not always know the runner's leading foot during acquisition, unless it is one of the experimental goals to assess specific legs dictating the need to observe and identify the leading leg.

III. RESULTS AND DISCUSSION

The presented algorithm showed accurate and satisfactory results in terms of leg-specific signal separation, and did not misinterpret or vary the content of the signals. This is due to the fact that the designed algorithm does not apply any functions upon the data; it only segments it according to precise rules. A sample of the computed results is shown in Fig.5, where the baseline shows the zero-padding that fills the inter-step period and the complementary aspect of the two signals is clear.

The main purpose behind the presented work is highlighted in the presented results, where the difference in pattern and in amplitude between the two different legs' VGRF shows clear asymmetry that is quantifiable and interpretable. The same algorithm was applied to the 120 signals, which ended up in 240 total time series representing separated leg-specific VGRF signals to be exploited further.

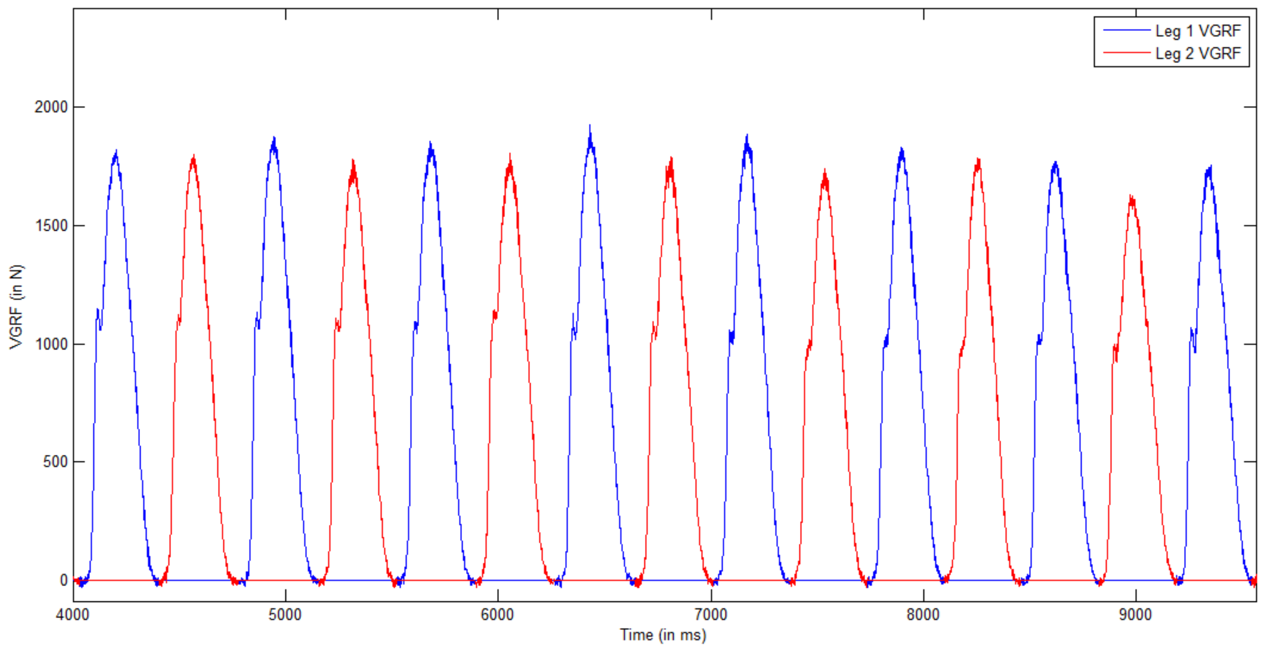

Figure 5. Separated Leg-specific VGRF Signals.

IV. CONCLUSION

This work presented an essential algorithm that may be used to process single-channel VGRF signals before any analysis scheme. The isolation of leg-specific signals may be used in physiotherapy for assessment of inter-leg symmetry, as well as in athletic performance tracking. Future work shall make use of the computed results to assess marathon runners' fatigue having leg asymmetry as main index.

ACKNOWLEDGMENT

The authors would like to thank S. Berjaoui, the director of Mechanical Engineering laboratories and faculty member at Rafik Hariri University for sharing his thoughts and providing technical assistance during the period of this research.

REFERENCES

[1] T.S. Keller, A.M. Weisberger, J.L. Ray, S.S. Hasan, R.G. Shiavi, and D.M. Spengler, "Relationship between vertical ground reaction force and speed during walking, slow jogging, and running", *Clinical Biomechanics*, vol.11, 1996, pp. 253-259.

[2] M. Hadizadeh, S. Amri, SA. Roohi and AH. Mokhtar, «Gait analysis of national athletes after anterior cruciate ligament reconstruction following three stages of rehabilitation program: Symmetrical perspective", *Gait and Posture*, vol.48, 2016, pp.152-158.

[3] M. Hadizadeh, S. Amri, SA. Roohi and H. Mohafez, «Assessment of Gait Symmetry Improvements in National Athletes after Anterior Cruciate Ligament Reconstruction during Rehabilitation", *International Journal of Sports Medicine*, vol.37(12), 2016, pp.997-1002.

[4] D. Fineberg, P. Asselin, N. Harel, I. Agranova-Breyter, S. Kornfeld, W. Bauman, and A. Spungen, "Vertical ground reaction force-based analysis of powered exoskeleton-assisted walking in persons with motor-complete paraplegia", *Journal of Spinal Cord Medicine*, 36(4), July 2013, pp.313-321.

[5] A. Belli, P. Bui, A. Berger, A. Geyssant, and J.R. Lacour, « A treadmill ergometer for three-dimensional ground reaction forces measurement during walking", *Journal of Biomechanics*, vol.34, 2001, pp.105-112.

[6] A. Voloshina, and D. Ferris, "Biomechanics and energetics of running on uneven terrain", *Journal of Experimental Biology*, vol.218, 2015, pp.711-719.

[7] A. Tongen, and R. Wunderlich, "Biomechanics of Running and Walking", *Mathematics and Sports*, 2010, 313-325.

[8] A. Zadpoor, and A. Nikoovan, "The effects of lower extremity muscle fatigue on the vertical ground force: a meta-analysis:, 226(8), August 2012, pp.579-288.

[9] BJ. Wallace, TW. Kernozek, JM. White, DE. Kline, GA. Wright, HT. Peng, CF. Huang, "Quantification of vertical ground reaction forces of popular bilateral plyometric exercises", *Journal of Strength and Conditioning Research*, vol.24(1), January 2010, p.207-212.

[10] C.F. Munro, D.I. Miller, A.J. Fuglevand, "Ground Reaction Forces in Running: A Reexamination", *Journal of Biomechanics*, vol.20(2), 1987, pp.147-155.

[11] J. Gottschall, R. Kram, "Ground reaction forces during downhill and uphill running", *Journal of Biomechanics*, vol.38, 2005, pp.445-452.