Journal of Biomechanics - Short Communication

# Ratio of forces during sprint acceleration: a comparison of different calculation methods

Neil Bezodis[1], Steffi Colyer[2], Ryu Nagahara[3], Helen Bayne[4], Ian Bezodis[5], Jean-Benoît Morin[6], Munenori Murata[3], Pierre Samozino[7]

[1] Applied Sports, Technology, Exercise and Medicine Research Centre, Swansea University, UK. ORCID: 0000-0003-2229-3310.

[2] Department for Health, University of Bath, UK. ORCID: 0000-0002-4973-6591.

[3] National Institute of Fitness and Sports in Kanoya, Japan. ORCID: 0000-0001-9101-9759 (Nagahara).

[4] Department of Physiology, Faculty of Health Sciences, University of Pretoria, South Africa. ORCID: 0000-0002-2520-4937.

[5] Cardiff School of Sport & Health Sciences, Cardiff Metropolitan University, UK. ORCID: 0000-0002-0250-032X.

[6] UJM-Saint-Etienne, Interuniversity Laboratory of Human Movement Biology, EA 7424, University of Lyon, Saint-Étienne, France. ORCID: 0000-0003-3808-6762.

[7] Univ Savoie Mont Blanc, Interuniversity Laboratory of Human Movement Biology, EA 7424, F-73000 Chambéry, France. ORCID: 0000-0002-1665-870X.

Corresponding author: Dr Neil Bezodis, Swansea University Bay Campus, Crymlyn Burrows, Swansea, Wales, UK, SA1 8EN.

Word count: 2,147 words.

**Abstract**

The orientation of the ground reaction force (GRF) vector is a key determinant of human sprint acceleration performance and has been described using ratio of forces (RF) which quantifies the ratio of the antero-posterior component to the resultant GRF. Different methods have previously been used to calculate step-averaged RF, and this study therefore aimed to compare the effects of three calculation methods on two key "technical" ability measures: decline in ratio of forces ($D_{RF}$) and theoretical maximal RF at null velocity ($RF_0$). Twenty-four male sprinters completed maximal effort 60 m sprints from block and standing starts on a fully instrumented track (force platforms in series). RF-horizontal velocity profiles were determined from the measured GRFs over the entire acceleration phase using three different calculation methods for obtaining an RF value for each step: A) the mean of instantaneous RF during stance, B) the step-averaged antero-posterior component divided by the step-averaged resultant GRF, C) the step-averaged antero-posterior component divided by the resultant of the step-averaged antero-posterior and vertical components. Method A led to significantly greater $RF_0$ and shallower $D_{RF}$ slopes than Methods B and C. These differences were very large (Effect size Cohen's d = 2.06 – 4.04) and varied between individuals due to differences in the GRF profiles, particularly during late stance as the acceleration phase progressed. Method B provides RF values which most closely approximate the mechanical reality of step averaged accelerations progressively approaching zero and it is recommended for future analyses although it should be considered a *ratio of impulses*.

Abstract word count: 250 words.

**Keywords**: ground reaction force, impulse, sprinting, technique.

## Introduction

The magnitude and orientation of the ground reaction force (GRF) vector is a key determinant of human sprint acceleration performance. GRF orientation has been quantified by the ratio of forces (RF: ratio of the antero-posterior component to the resultant GRF) as a measure of mechanical effectiveness since it was first proposed by Morin et al. (2011). This provides a valuable measure of a sprinter's ability to apply force in a more horizontal direction. For the same magnitude of force applied by a sprinter, the horizontal change in velocity during stance – which ultimately affects performance – will differ based on the orientation of the resultant GRF vector.

One prevalent use of RF data has been to establish how a sprinter's RF decreases as horizontal velocity ($v_H$) increases across the entire acceleration phase, with this relationship well fitted by a linear approximation (Morin et al., 2012; 2019; Rabita et al., 2015; Samozino et al., 2016). The gradient of this linear fit is extracted as a measure of the rate of decline in ratio of forces ($D_{RF}$). The y-intercept can be obtained as a measure of the theoretical maximal RF at null velocity ($RF_0$; Rabita et al., 2015), or other measures of the relative location of this trendline are also sometimes used such as the value at 0.3 s into the sprint ($RF_{MAX}$) to represent the RF value during the initial push-off (Samozino, 2018; Samozino et al., 2016).

Whilst measures extracted from the RF-$v_H$ trendline have been increasingly used in applied practice and research (Hicks et al., 2020), the input data used to determine step-averaged RF have not been consistent between studies. 'Step-averaged' is used as a descriptor throughout for ease of reading; some methods can only use data during stance as there is no GRF and thus no RF during flight, whilst others have previously used average forces from either just stance or the entire step but this does not affect the determined RF value. For example, Morin et al. (2011, 2012) used the ratio between the mean antero-posterior component and the mean resultant GRF over each contact period, Rabita et al. (2015) used the mean value of the instantaneous RF over each contact period, and Samozino et al. (2016) and Morin et al. (2019) used the ratio between the step-averaged antero-posterior component and the resultant of the step-averaged antero-posterior and vertical components. Although conceptually close, these methods are all computationally different and will not necessarily yield the same value for step-averaged RF. We therefore aimed to determine the effects of calculating step-averaged RF using each of the above three methods on the widely used properties of the RF-$v_H$ relationship (i.e. $D_{RF}$ and $RF_0$), with a view to determining whether they can be used interchangeably and, if not, to discuss the relative merits of each.

**Methods**

Following ethical approval and the provision of informed consent, 24 male sprinters (age = 20 ± 1 years; stature = 1.73 ± 0.06 m; mass = 65.7 ± 4.0 kg; 100 m personal best = 11.26 ± 0.39 s) completed two maximal effort 60 m indoor sprints from a standing start and two from starting blocks. All sprinters wore their own spiked shoes and used their preferred block settings. A 52-m series of force platforms (TF-3055, TF-32120, TF-90100, Tec Gihan, Uji, Japan) was located under the track from which raw GRF data were collected at 1000 Hz. The start of data capture was synchronised with the starting signal and data capture was manually stopped after the sprinter had run 52 m. Standing and block starts were included because both are used by track sprinters at different phases within the season but the determination of these performance metrics (e.g. $D_{RF}$, $RF_0$) often happens year-round. These metrics are also widely used in team sports athletes who start from standing, and thus the separate consideration of effects for both starting conditions yields greater value to the applied community.

The vertical and antero-posterior components of the GRF data were low-pass filtered at 70 Hz, and instantaneous horizontal velocity was determined using the impulse-momentum relationship accounting for the influence of air resistance (Samozino et al., 2016; Colyer et al., 2018). Instantaneous RF was determined from the antero-posterior and vertical components of the filtered GRF data as the ratio of the antero-posterior component to the 2D resultant. Given our aim, the two-dimensional (sagittal plane) representation of the GRF vector was used to be consistent with the previous studies which have determined RF in sprinting, and the effects of including the medio-lateral component in the resultant magnitude are negligible (Rabita et al., 2015). Movement onset was identified from the raw antero-posterior GRF using a two standard deviation threshold for the block starts. The same procedure was initially applied to the standing starts but because of considerable variation in the standing start technique between sprinters, visual identification by an experienced analyst was used for all standing start trials so that minor fluctuations associated with preparatory movements were ignored and the first clear and sustained increase in force was identified. All subsequent touchdown and toe-off events were identified using a 25 N threshold in the vertical GRF data.

Step-averaged RF was determined from the block exit/initial push-off step to the final step on the force platforms using each of three different methods in line with this study's aims:

A. The mean value of instantaneous RF over the whole stance phase (Rabita et al., 2015).
B. The step-averaged antero-posterior component divided by the step-averaged resultant (2D sagittal) GRF (Morin et al., 2011; 2012).
C. The step-averaged antero-posterior component divided by the resultant of the step-averaged antero-posterior and vertical components (Samozino et al., 2016; Morin et al., 2019).

To determine the relationships between RF and $v_H$ for each of the above three methods, average $v_H$ from the corresponding time interval was used. For method A, $v_H$ was averaged over just the stance phase, whereas for methods B and C $v_H$ was determined from touchdown to the next touchdown (this was done to enable a direct comparison between methods B and C and had only a minor influence on the $v_H$ values between these and Method A, and therefore on the outcome of this study, see Figure 1). For each of the three methods, linear trendlines were fitted over the entire acceleration phase from the initial block exit/push-off to the step with the highest velocity (mean ± SD = step 24 ± 2 for block starts; step 23 ± 2 for standing starts), and $D_{RF}$ and $RF_0$ were extracted.

Mean values of the two trials for each sprinter in each condition (standing, blocks) were calculated. Twelve standing start trials (across nine sprinters) were rejected because the sprinter was deemed not stationary at the start signal and thus n = 21 for the standing start condition (values from one successful trial were used for six sprinters). $D_{RF}$ and $RF_0$ were compared between the three methods using a repeated-measures ANOVA with Bonferroni post hoc tests (alpha level = 0.05), and the systematic bias and random errors were quantified using a Bland-Altman analysis. Cohen's effect sizes (d) were used to describe the magnitude of the pairwise systematic bias based on the thresholds proposed by Hopkins et al. (2009) of 0.2, 0.6, 1,2 and 2.0 for small, moderate, large and very large, respectively.

**Results**

For both block and standing starts, there was a significant main effect of calculation method on $D_{RF}$ and $RF_0$, with post-hoc tests revealing all three calculation methods yielded different values from one another for all comparisons (Table 1). The method using the mean of the instantaneous RF data (i.e. Method A) always had a lower $RF_0$ and a shallower $D_{RF}$ than methods B and C (Table 1, Figure 1).

****Figure 1 near here****

The random differences (i.e. 95% limits of agreement) were always larger for Method C compared with Method A than for Method B compared with Method A (Figure 2; Table 2). All effect size differences for comparisons with Method A were very large, whilst the effect size differences between Methods B and C ranged from trivial to moderate (Table 2).

**Table 1.** Theoretical maximal RF at null velocity ($RF_0$) and rate of decline in RF ($D_{RF}$) for block starts and standing starts determined from the linear fit to ratio of forces (RF) and horizontal velocity data using step-averaged RF data from each of the three different calculation methods (mean ± SD).

| | Method A: using step-averaged RF determined as the mean of the instantaneous RF data | Method B: using step-averaged RF determined from step-averaged A-P GRF and step-averaged resultant GRF | Method C: using step-averaged RF determined from step-averaged A-P GRF and step-averaged vertical GRF | ANOVA results |
|---|---|---|---|---|
| Block starts | | | | |
| $RF_0$ (%) | 64.70 ± 2.69 $^{B,C}$ | 72.01 ± 3.01 $^{A,C}$ | 73.94 ± 3.15 $^{A,B}$ | $F(2,46) = 616.180$, $\eta^2_{partial} = 0.964$, $p<0.001$ |
| $D_{RF}$ (%·s/m) | -5.64 ± 0.45 $^{B,C}$ | -7.21 ± 0.44 $^{A,C}$ | -7.38 ± 0.45 $^{A,B}$ | $F(2,46) = 1372.107$, $\eta^2_{partial} = 0.984$, $p<0.001$ |
| Standing starts | | | | |
| $RF_0$ (%) | 63.71 ± 3.58 $^{B,C}$ | 71.20 ± 3.67 $^{A,C}$ | 72.28 ± 3.71 $^{A,B}$ | $F(2,40) = 295.925$, $\eta^2_{partial} = 0.937$, $p<0.001$ |
| $D_{RF}$ (%·s/m) | -5.44 ± 0.42 $^{B,C}$ | -7.06 ± 0.42 $^{A,C}$ | -7.13 ± 0.42 $^{A,B}$ | $F(2,40) = 662.767$, $\eta^2_{partial} = 0.971$, $p<0.001$ |

Note: superscript A, B, C = significantly different (all p < 0.001) from method A, B or C, respectively, in pairwise post-hoc comparisons with Bonferroni adjustment.

**Table 2.** Systematic bias ± 95% limits of agreement (and Cohen's d effect size) for each pairwise comparison of methods for both $RF_0$ and $D_{RF}$ from block starts and standing starts.

$RF_0$ (%) – block starts

| | Method B | Method C |
|---|---|---|
| Method A | 7.30 ± 3.01 (d = 2.56) | 9.23 ± 3.39 (d = 3.15) |
| Method B | - | 1.93 ± 0.84 (d = 0.63) |

$RF_0$ (%) – standing starts

| | Method B | Method C |
|---|---|---|
| Method A | 7.48 ± 4.02 (d = 2.06) | 8.57 ± 4.36 (d = 2.35) |
| Method B | - | 1.08 ± 0.58 (d = 0.29) |

$D_{RF}$ (%·s/m) – block starts

| | Method B | Method C |
|---|---|---|
| Method A | -1.57 ± 0.41 (d = 3.53) | -1.74 ± 0.45 (d = 3.86) |
| Method B | - | -0.17 ± 0.09 (d = 0.39) |

$D_{RF}$ (%·s/m) – standing starts

| | Method B | Method C |
|---|---|---|
| Method A | -1.62 ± 0.56 (d = 3.89) | -1.70 ± 0.59 (d = 4.04) |
| Method B | - | -0.08 ± 0.06 (d = 0.18) |

****Figure 2 near here****

## Discussion

The method used to determine step-averaged RF has a significant effect on the determined $D_{RF}$ and $RF_0$ measures. There is a systematic component to these differences, with Method yielding lower $RF_0$ and shallower $D_{RF}$ measures than Methods B and C for all trials from both types of start (Figure 2a,b,d,e). These differences were very large based on the effect sizes, and their magnitude should be considered important in the context of typical between-participant variation (Haugen et al., 2019) or within-participant change in response to training (Lahti et al., 2020). Method B always had a lower $RF_0$ and a shallower $D_{RF}$ than Method C, although these differences were considerably smaller than those compared with Method A, ranging from trivial to moderate (Figure 2c,f). In addition to these systematic effects, there were also considerable random differences as illustrated by the 95% limits of agreement (Figure 2). These demonstrate that the magnitude of the differences between the three methods varies from one sprinter to the next, and thus a simple systematic offset to convert between methods is not appropriate.

The systematic differences in $D_{RF}$ and $RF_0$ between Method A and the other two methods primarily occur because of differences in the sequence of calculations (i.e. when values are squared and averaged). Individual differences in the shape of the GRF profiles produced during stance and the consequent effects on the instantaneous RF profile explain the random differences, particularly during late stance when GRF magnitudes are relatively low and RF can reach high values (Figure 3). Given the nature of the calculations used in Method A, the instantaneous RF values during late stance have an equal weighting to all other timepoints despite occurring when the GRF is less “functionally effective” due to it already being low and decreasing further. The effects of this on step-averaged RF become increasingly more pronounced as the acceleration phase progresses (Figure 1). This may be due to the average RF being higher up to around mid-stance during early acceleration than mid-acceleration (i.e. step 1 vs. step 13; Figure 3) or because the rate of decline in the horizontal GRF component during late stance becomes relatively lower than that of the vertical component as the acceleration phase progresses (i.e. step 13 vs. step 1; Figure 3), potentially because of the changing late stance kinematics with the trunk more upright and the hip more extended later in the acceleration phase (Schache et al., 2019). Method A is the most mathematically appropriate as a direct measure of mean RF. However, step averaged accelerations are further from zero than Methods B and C at the end of the acceleration phase, and thus its applied mechanical meaning is less clear.

****Figure 3 near here****

Although the differences between Methods B and C were only trivial to moderate, they yielded different outputs from each other because of differences in the calculation approach. Method C should not be used when GRFs are available because mean horizontal force and mean vertical force should not be used to determine mean resultant force. However, this is the only computation method possible when using simple modelled values from a macroscopic approach (Samozino et al., 2016; Morin et al., 2019) and it therefore provides a viable alternative for field-based assessment given the magnitude of the differences reported.

Method B is a *ratio of impulses* rather than a ratio of forces. This method provides values closer to the mechanical reality of step averaged accelerations approaching zero (aside from air resistance effects) at the end of the acceleration phase. Method B therefore provides a more appropriate assessment of "mechanical effectiveness" over an entire step than Method A as it is not overly affected by nuances in the GRF profile during late stance when force production is low, particularly later in the acceleration phase. Instantaneous RF data, as used in Method A, may still provide valuable information when within-stance technique is of interest (e.g. Bezodis et al., 2019; Colyer et al., 2018) but caution should be applied to over-interpretation of RF values when GRF magnitudes are low.

The method used to determine step-averaged RF affects the determination of measures related to "mechanical effectiveness" in sprinting. Researchers and coaches must apply caution to the interpretation and comparison of results depending on which calculation method was employed. Using instantaneous RF data (Method A) leads to step-averaged RF values which are further from mechanical reality as a sprint progresses, but instantaneous RF data may be useful when focusing on within-stance technique. The resultant of the step-averaged antero-posterior and vertical components should only be used as the denominator (Method C) in simple macroscopic models when GRF data are unavailable. The use of step-averaged antero-posterior and resultant (2D) force magnitudes (Method B) is recommended to assess "mechanical effectiveness" in sprinting as this provides data closer to the mechanical reality, but these data are a *ratio of impulses* due to the nature of their calculation.

**Conflict of interest statement**

None of the authors have any financial or personal relationships with other people or organisations that could inappropriately influence this work.

**References**

Bezodis, N. E., Walton, S. P., & Nagahara, R. (2019). Understanding the track and field sprint start through a functional analysis of the external force features which contribute to higher levels of block phase performance. *Journal of Sports Sciences*, *37*(5), 560-567.

Colyer, S. L., Nagahara, R. & Salo, A. I. T. (2018). Kinetic demands of sprinting shift across the acceleration phase: novel analysis of entire force waveforms. *Scandinavian Journal of Medicine and Science in Sports*, *28*(7), 1784-1792.

Haugen, T. A., Breitschädel, F., & Seiler, S. (2019). Sprint mechanical variables in elite athletes: Are force-velocity profiles sport specific or individual? *PLoS ONE*, *14*(7), e0215551.

Hicks, D. S., Schuster, J. G., Samozino, P., & Morin, J.-B. (2020). Improving mechanical effectiveness during sprint acceleration: practical recommendations and guidelines. *Strength and Conditioning Journal*, *42*(2), 45-62.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3–13.

Lahti, J., Jiménez-Reyes, P., Cross, M. R., Samozino, P., Chassaing, P., Simond-Cote, B., Ahtiainen, J. P., & Morin, J.-B. (2020). Individual sprint force-velocity profile adaptations to in-season assisted and resisted velocity-based training in professional rugby. *Sports*, *8*(5), 74.

Morin, J.-B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise*, *43*(9), 1680-1688.

Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P. & Lacour, J.-R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, *112*(11), 3921-3930.

Morin, J.-B., Samozino, P., Murata, M., Cross, M. R. & Nagahara, R. (2019). A simple method for computing sprint acceleration kinetics from running velocity data: replication study with improved design. *Journal of Biomechanics*, *94*, 82-87.

Rabita, G., Dorel, S., Slawinski, J., Saez-de-Villarreal, E., Couturier, A., Samozino, P. & Morin J.-B. (2015). Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scandinavian Journal of Medicine and Science in Sports*, *25*(5), 583-594.

Samozino, P. (2018). A simple method for measuring force, velocity and power capabilities and mechanical effectiveness during sprint running. In J.-B. Morin & P. Samozino (Eds), *Biomechanics of Training and Testing* (pp. 237-267). Cham, Switzerland: Springer International Publishing.

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., Saez de Villarreal, E. & Morin, J.-B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine and Science in Sports*, *26*(6), 648-658.

Schache, A. G., Lai, A. K. M., Brown, N. A. T., Crossley, K. M. & Pandy, M. G. (2019). Lower-limb joint mechanics during maximum acceleration sprinting. *Journal of Experimental Biology*, *222*(22), jeb209460.

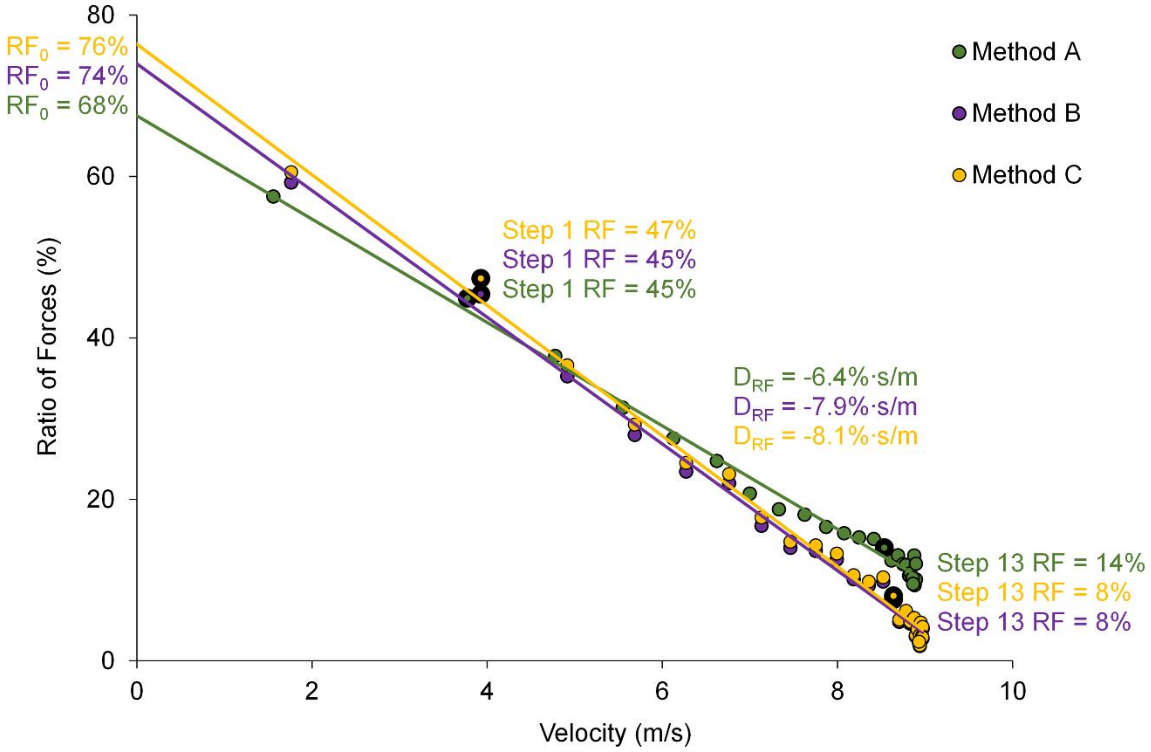


**Figure 1.** Ratio of forces-horizontal velocity relationships compared between the three calculation methods for a typical trial from blocks for one participant. These relationships are fitted to all data from the initial block exit/push-off to the step with the highest average horizontal velocity. The stated step 1 and step 13 step-averaged RF values correspond to the respective data points with a bold outline (note: for step 13 the values for methods B and C are very close). These bold data points correspond to the continuous GRF data in Figure 3 which illustrate reasons for the differences between the methods as the acceleration phase progresses.

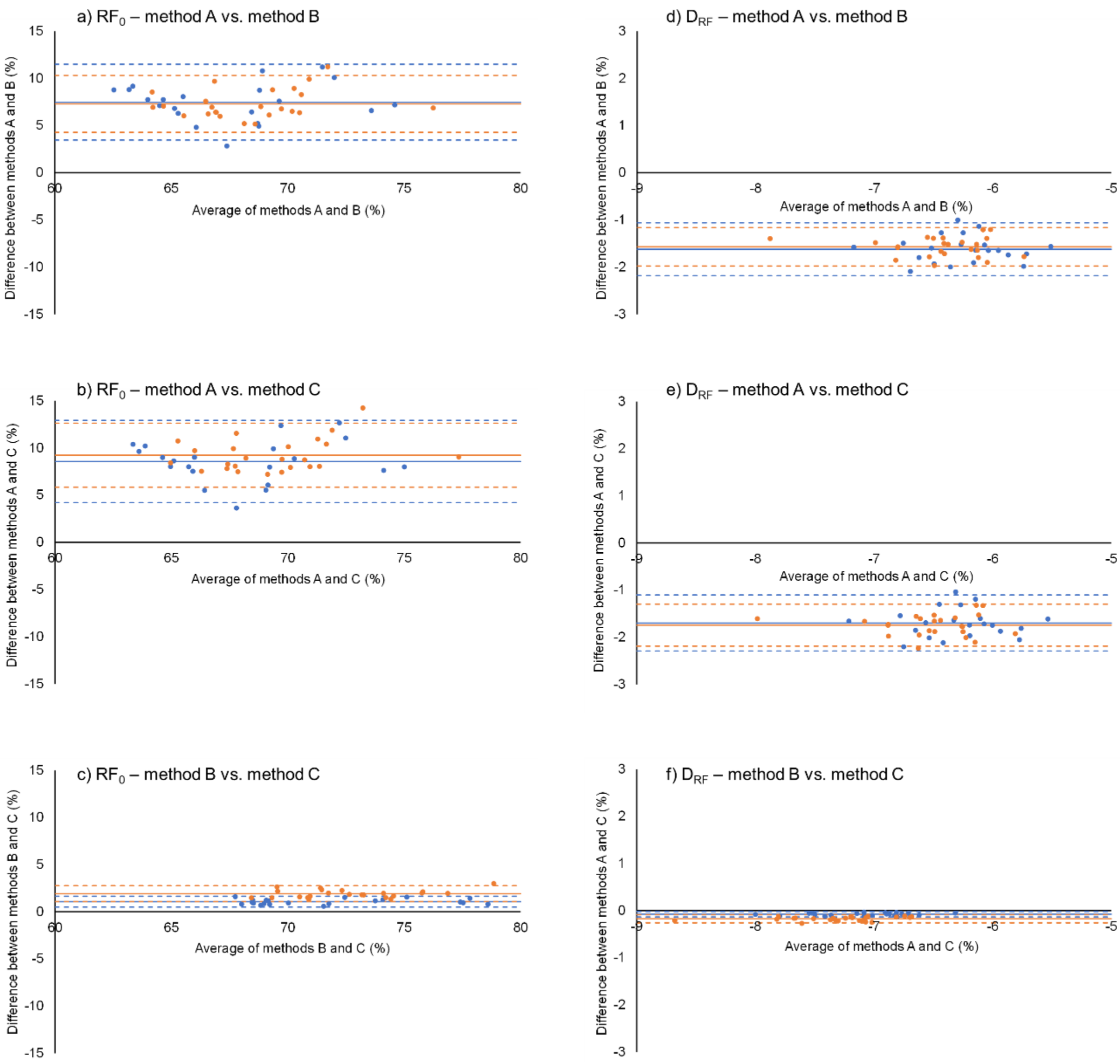


**Figure 2.** Bland-Altman plots for $RF_0$ and $D_{RF}$ between each pairwise comparison of the three methods. Block start trials are shown in orange and standing start trials are shown in blue. All axes are scaled the same for each variable for ease of comparison between figures.

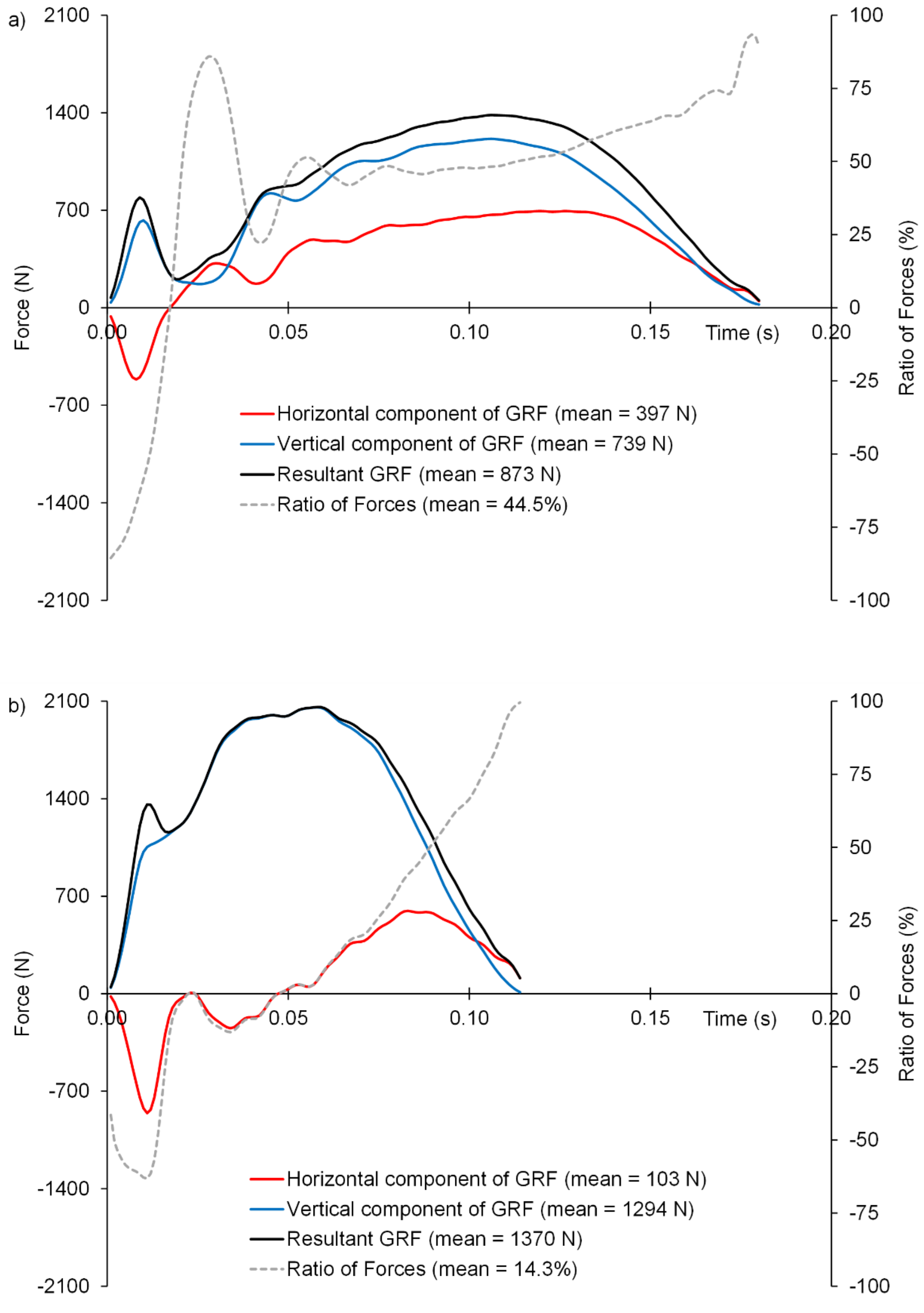


**Figure 3.** Vertical and horizontal components of the ground reaction force, resultant ground reaction force (2D sagittal), and instantaneous ratio of forces (plotted on secondary y-axis) during a) step 1 and b) step 13 for a typical trial from blocks. Note: this is the same trial as the data presented in Figure 1 (in which data points corresponding to steps 1 and 13 are identified with a bold outline).