INTER-LIMB ASYMMETRY DURING REHABILITATION

UNDERSTANDING FORMULAS AND MONITORING THE "MAGNITUDE" AND "DIRECTION"

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INTRODUCTION

Monitoring and reporting inter-limb asymmetry during rehabilitation has been a common line of investigation[2,15,22,28,29,31]. Between-limb deficits in strength have been reported[11,18,22,32] and the use of horizontal hop tests have been a popular choice to detect residual side-to-side differences in functional performance[2,15,20,22,28,31]. With strength and power typically seen as two of the most important physical qualities for athletic performance,[16,35,36] it is not surprising that asymmetries in these two physical qualities are frequently tested during injury rehabilitation to determine an individual's state of readiness to return to sport[2,18,22,28].

A key focal point of returning an athlete to their chosen sport is often to reduce and potentially minimize inter-limb asymmetry during rehabilitation. Given that often an obvious between-limb deficit exists when an athlete is injured, progressively enhancing the capacity of the injured limb can be seen as a "window of opportunity" for physical training and conditioning[19,26]. In addition, with such an obvious between-limb difference present, the direction of asymmetry is likely to be consistent. That is to say, the uninjured limb is likely to most frequently produce the best score compared to the injured side. However, recent findings (albeit in healthy populations) have suggested that both the magnitude and direction of asymmetry are both highly variable and task-specific[4,6,12,25]. Monitoring the magnitude of asymmetry alone may hinder a practitioners' ability to use this information as part of the ongoing monitoring process, especially when athletes are nearing return to participation, and once they have returned to full competitive activities. Thus, considering both the magnitude and direction of asymmetry may provide a clearer understanding of which deficits are consistent or natural fluctuations in performance variability due to training load adaptations and normal movement variability.

Choosing the most appropriate formula to calculate inter-limb asymmetry is also an important consideration. Previous literature has highlighted that multiple formulas exist to calculate inter-limb differences[5,7], which poses challenges for practitioners given that the reason why one formula should be chosen over another is often not obvious. From an injury perspective, limb symmetry

Table 1

Asymmetry Name	Formula	Asymmetry (%)	Reference
Limb Symmetry Index 1	(Inv/un-Inv)*100	87.5	Logerstedt et al[24]
Limb Symmetry Index 2	(1–Inv/un-Inv)*100	12.5	Schiltz et al[33]
Limb Symmetry Index 3	(R–L)/0.5(R+L)*100	13.3	Bell et al[3]
Bilateral Strength Asymmetry	(Strong–Weak)/Strong*100	12.5	Impellizzeri et al[19]
Bilateral Asymmetry Index 1	(D–ND)/(D+ND)*100	6.7	Kobayashi et al[21]
Bilateral Asymmetry Index 2	(2*(D–ND)/(D+ND))*100	13.3	Wong et al[38]
Asymmetry Index	(D–ND)/(D+ND/2)*100	13.3	Robinson et al[30]
Symmetry Index	(High–Low)/Total*100	6.7	Shorter et al[34]
Symmetry Angle	(45–arctan(L/R))/90*100	4.2	Zifchock et al[39]
Standard Percentage Difference	100/(Max)*(Min)*-1+100	12.5	Bishop et al[7]

Inv = involved; un-Inv = un-involved; R = right; L = left; D = dominant; ND = non-dominant.

Table 1: Inter-limb asymmetry formulas and values using a hypothetical example of peak force during a CMJ. N.B: 800 N=un-involved, right, strong, high and dominant limb; 700 N=involved, left, weak, low and non-dominant limb.

index (LSI) formulas have often been used to quantify existing between-limb deficits throughout the rehabilitation process. Intuitively, this makes sense given that the injured limb is likely to produce a lower score. However, when an athlete is nearing return to play (RTP), it is possible that the injured limb may actually display heightened performance relative to the uninjured limb, which can compromise calculating the magnitude of asymmetry and where complications in the formulas arise (discussed later). This further highlights the need for a consistent approach to calculating between-limb differences, considering both the magnitude and direction of asymmetry regardless of what stage of rehabilitation the athlete is at.

The aims of this article are to first highlight key considerations regarding the formulas selected for calculating the magnitude of asymmetry during injury rehabilitation and secondly, propose an evidence-based justification for monitoring both the magnitude and direction of asymmetry during the rehabilitation process.

MONITORING THE MAGNITUDE OF ASYMMETRY AND DIFFERENTIATING BETWEEN TEST METHODS
Choosing an appropriate formula
Using Table 1, we propose a hypothetical example whereby peak force asymmetry is measured during a countermovement jump (CMJ). In this example, the reader is asked to assume that 800 N corresponds to the uninjured, dominant, right and stronger limb. There is of course no guarantee that this will always be the case, but should be assumed purely for the purpose of illustrating this point. Before deciding which formula to use, first we must consider the notion of how standard percentage differences are calculated. To do this, understanding how fractions of 100 are computed is important, noting that traditional mathematics only teaches this one way (i.e., in relation to the maximum value) and that difference then gets expressed as a percentage of 100. Thus, with standard percentage differences quantifying between-limb deficits relative to the maximum value, Table 1 highlights three formulas which calculate our hypothetical peak force

asymmetry value in such a way: Bilateral Strength Asymmetry, Symmetry Index and the Standard Percentage Difference method. The Bilateral Strength Asymmetry and Standard Percentage Difference equations are set up to always calculate the percentage difference the same way, noting that the equations themselves do not change, just the raw data that goes into them. In addition, the reader should note that these formulas do not consider the total value generated by both limbs; therefore, these can only be considered when calculating inter-limb asymmetry from unilateral test methods.

Table 1 also shows that many different approaches have been adopted when calculating inter-limb differences. Injury based research typically uses terms such as 'involved' and 'un-involved' when reporting limb differences; thus, the LSI-1 and LSI-2 formulas are commonly used to quantify between-limb deficits. In addition, the reader could look at Table 1 and think that the LSI-2 formula could be used to calculate asymmetry from unilateral test protocols, noting that the percentage value is the same as the Bilateral Strength

Asymmetry and Standard Percentage Difference equations. However, it is likely that this is only consistent when an athlete is injured, because an obvious reason exists for the between-limb asymmetry (i.e., one limb is injured). For athletes that have been rehabilitated post-injury, trained consistently over an extended period of time and successfully returned to competition; the reason for existing side-to-side differences becomes less apparent. In fact, it is plausible that a previously injured limb may perform superiorly over time, in which case, complications in the formulas can arise. To prove this point, if we swap the peak force values around in that second equation from Table 1 so that the un-involved limb now scores 700 N instead of 800 N, the asymmetry value becomes -14.3%. The negative sign tries to tell us that the involved limb produced greater peak force; however, it has compromised the magnitude of asymmetry (12.5%), which was previously determined from our standard percentage difference. In addition, given the absolute force difference measured between limbs has not changed (i.e., 100 N), the percentage difference should not be altered. Thus, not all equations may be robust enough to withstand every scenario that are presented to practitioners when collecting data. Therefore, when calculating asymmetry from unilateral tests, the formulas proposed by Impellizzeri et al.[19] or Bishop et al.[7] are the suggested options.

During a bilateral CMJ, if practitioners wish to quantify between-limb differences in peak force, it is suggested that the imbalance must be expressed relative to the sum total of force production given that both limbs are interacting together. The key point here being that if each limb is not acting independently, the quantification of imbalances should not be treated as separate entities. In contrast, during a unilateral CMJ there is no ground contact contribution from the other limb; thus, quantifying any existing side-to-side differences can be done without considering the opposing limb's involvement (noting that it has none). The formulas proposed by Kobayashi et al.[21] or Shorter et al.[34] calculate between-limb differences relative to the total value, remembering that this is suggested because both limbs are interacting together. Whilst other formulas also do this in Table 1 (e.g., Bell et al.[3], Wong et al.[38] and Robinson et al.[30]), there is no evidence to suggest that
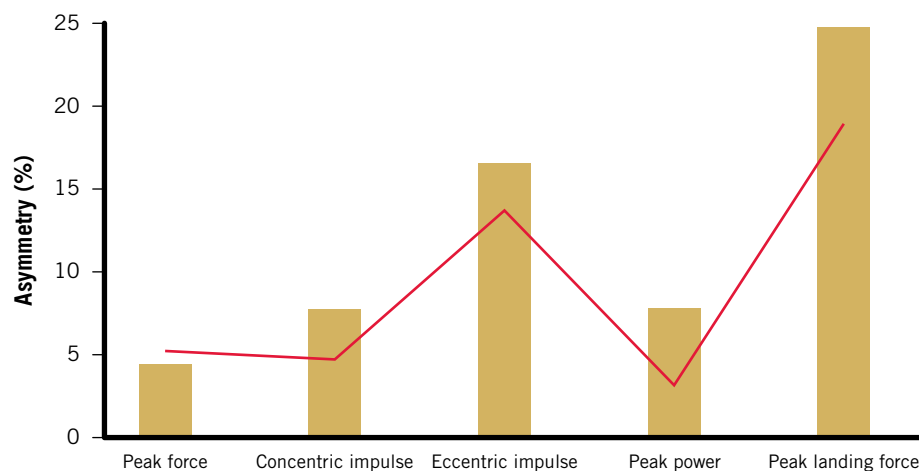

Figure 1: Hypothetical example showing the metric-specific nature of asymmetry (gold bars) during a countermovement jump in relation to the coefficient of variation (red line).

the asymmetry outcome should be altered anywhere in the formula by either dividing by 0.5, multiplying by 2 or dividing by 2 respectively. Thus, the proposed formulas for calculating inter-limb differences during bilateral tests are either the Symmetry Index or Bilateral Asymmetry Index 1.

Now that proposed formulas have been suggested for the quantification of asymmetries, it is important to realise that practitioners are merely left with a percentage value, known as the magnitude of asymmetry. Previous literature has suggested that magnitudes of 10-15% may increase the risk of an athlete getting injured and should be used as a minimum target for an athlete to 'pass' return to sport testing[2,22,28,31]. However, with an abundance of evidence to show that asymmetries are task and metric-specific[4,6,8,9,12,17,23,25], this notion appears rather superficial given that any magnitude could only be applied relative to the chosen test, metric or population in question. Thus, when left with the magnitude of asymmetry, it poses the question of how to interpret the data.

Interpreting the magnitude of asymmetry
An often overlooked component of asymmetry data interpretation is to examine and interpret the differences in the context of the typical error associated with the test. We must acknowledge that there is inherent error present in any test that we administer which can come from many sources. Thus, we need to be able to determine what is a 'real' asymmetry. Previously, Exell et al.[13] highlighted the need to consider intra-limb variability in

conjunction with the inter-limb difference value. In short, it was inferred that an asymmetry may only be considered real if it was greater than the variability in the test. Practically this can be measured in the form of the coefficient of variation (CV) which is determined by looking at the standard deviation relative to the mean, and then expressed as a percentage by multiplying by 100[37]. Previous literature has suggested that values < 10%[10] or 5%[1] can be considered as acceptable variability. However, practitioners are encouraged to determine these for their own groups of athletes due to variations in movement skill and training age (see Turner et al.[37]) for an example of how to do this). Despite any disagreement on a proposed threshold, it is accepted that the lower the CV value, the more reliable the test or metric[10,37].

Where asymmetry is concerned, reporting any existing side-to-side differences in conjunction with test variability (i.e., the CV) may help to differentiate between 'the signal and the noise'. Furthermore, both values are reported in percentages providing practitioners with an easy comparison between the two. When an athlete is injured, especially if the injury is severe, it is likely that between-limb differences will be much greater than the CV when testing protocols resume. As rehabilitation and functional performance progresses, the imbalance should reduce and practitioners may wish to use the CV value as a target to aim for as a threshold for inter-limb asymmetry. In essence, this helps provide an individualised threshold for each athlete during the rehabilitation process
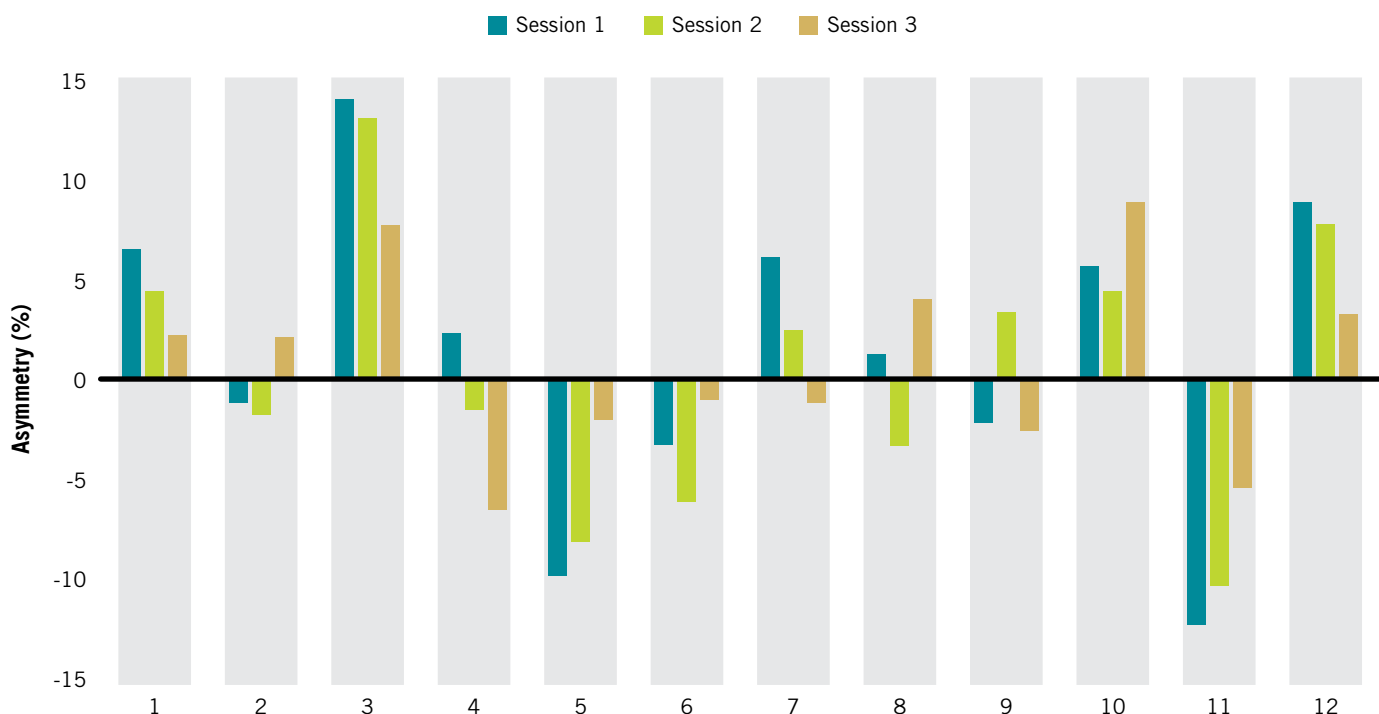
Figure 2: Hypothetical peak force asymmetry data for 12 athletes during a countermovement jump over three test sessions. Above 0 = asymmetry favours the dominant limb; below 0 = asymmetry favours the non-dominant limb.

and can be used for different metrics within the same test.

Figure 1 shows hypothetical asymmetry data (gold bars) for five metrics in a CMJ test, with the CV mapped on as a red line. Peak force is the only metric exhibiting asymmetry smaller than the CV; however, in this instance, not all metrics may be usable. Eccentric impulse and peak landing force are exhibiting inter-limb asymmetries of 16.6 and 24.8% respectively, both of which are greater than the CV. However, with CV's of 13.7 and 18.9%, the reliability of these metrics could be questioned[1,10,37]. Thus, although it has been suggested that the CV can be used to aid interpretation of asymmetry and as a potential target when reducing imbalances during rehabilitation, it is imperative to appreciate that if the CV is high (i.e., > 10%), practitioners may wish to be mindful of using such data to help inform the decision-making process due to the pronounced variability in the way the task is being executed by the injured athlete.

ADDING "DIRECTION" TO ASYMMETRY
Recent literature has highlighted the importance of the direction of asymmetry[26], which refers to the consistency of asymmetry favouring one side (i.e., right vs. left or dominant vs. non-dominant). As previously mentioned, when an athlete is injured, an obvious between-limb deficit is present; thus, the direction of asymmetry is likely to always favour the uninjured limb. However, when athletes are healthy or nearing RTP, the consistency of asymmetry may be lower and using the magnitude alone may be missing a piece of the puzzle when reporting an athlete's between-limb deficits.

This notion is supported in recent research by Bishop et al.[4,6] who showed the direction of asymmetry (i.e. the same limb being recognised as the highest performer) to be just as variable as the magnitude in healthy athletes. Specifically, peak vertical ground reaction force displayed low agreement across different strength and jumping tests used (again indicating the task dependent nature of asymmetry)[4]. In addition, analysis of the consistency of asymmetry favouring the same 'dominant' limb between separate test sessions in a unilateral isometric squat, CMJ and drop jump (DJ) tests often indicated only fair to moderate levels of agreement[6]. This has led to recent suggestions that the interpretation of inter-limb asymmetry should be done on an individual basis, rather than using

the group mean value as a guide[4,6]. Figure 2 shows an example of hypothetical data for peak force asymmetry during a CMJ being recorded over three test sessions for 12 participants. Values above 0 favour the dominant limb and below 0 favour the non-dominant limb, providing a clear distinction in the direction of asymmetry (Figure 2).

Therefore, and remembering that some equations provide the direction of asymmetry (by creating a negative value) but also compromise the magnitude, practitioners need a formula which is consistent to calculate both the magnitude and direction of asymmetry throughout the entire 'rehabilitation journey'. This can be done by adding an 'IF function' to the end of the relevant formula in Microsoft Excel: *IF(D<ND,1,-1). Simply put, this tells the asymmetry value to become negative if the non-dominant limb is the larger value without changing the magnitude. Therefore, when aiming to monitor the direction of asymmetry, the following equations are suggested for bilateral and unilateral tests respectively:
- Bilateral tests:
  ((D–ND)/Total*100)*IF(D<ND,1,-1)
- Unilateral tests:
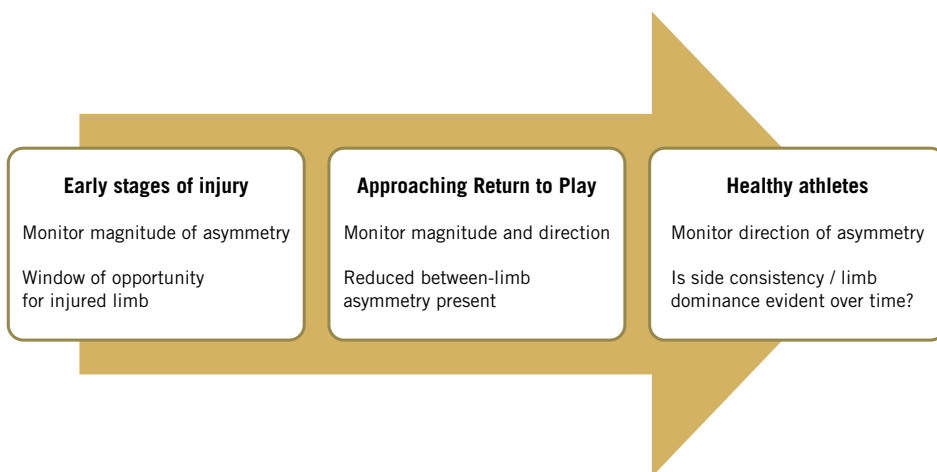 ((D–ND)/D*100)*IF(D<ND,1,-1)

Figure 3: Suggested approach for monitoring asymmetry during the rehabilitation process and once the athlete has returned to sport.

It is important to note that the above formulas are defining limbs via dominance which is a common method of differentiating performance between limbs[12,14,19,27]. However, practitioners can define limbs differently if desired (e.g., left vs. right or involved vs. un-involved) depending on which scenario suits their needs. From an injury perspective, replacing the dominant limb with 'un-involved' and the non-dominant limb with 'involved' would ensure that the magnitude of asymmetry is always computed relative to the maximum value when an obvious between-limb difference exists. In addition, the IF function will ensure that practitioners become aware if and when the involved limb surpasses the un-involved limb, providing a notable change in the direction of asymmetry. Thus, the process for monitoring both the magnitude and direction of asymmetry is suggested in Figure 3.

CONCLUSION
Calculating inter-limb asymmetries is perhaps more complex than we might think. The selection of an appropriate equation may depend on the nature of the test selected (e.g., bilateral or unilateral); however, it is essential that practitioners always keep in mind the needs of the athlete when selecting the most appropriate test. Owing to asymmetry being a variable concept, there is a need to be able to distinguish between the signal and the noise, which is why practitioners may wish to consider the CV to be useful when interpreting asymmetry scores. In addition, the use of a single asymmetry threshold (i.e. 10%) is likely not possible due to the task-specific and variable nature of measured

between-limb deficits. Finally, the use of an IF function in Microsoft Excel can enable the direction of asymmetry to be monitored without altering the magnitude, and should be considered as an additional tool in understanding the both the relevance and consistency of asymmetry throughout the rehabilitation journey, especially as athletes are nearing RTP.

References
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