Complementary Use of Wearable Technology 2: A Case Study in Gait Symmetry

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Headline

In the previous companion study (1), we showed that two wearable devices offer complementary data that describe distinct aspects of training load. In that investigation, we noted the work of Nasirzade et al. (2). They argued that running speed affects gait symmetry measures, particularly in patients with musculoskeletal abnormalities. This suggests that speed should be taken into consideration when evaluating measures such as step balance.

Aim

The goal of this investigation was to demonstrate the usefulness of combining wearable technology devices to gain a more complete understanding of gait symmetry. To accomplish this, we examined gait symmetry in an athlete during rehabilitation from anterior cruciate ligament (ACL) reconstruction.

Method

Data were collected on a single member of a Division I NCAA women's soccer team, after institutional approval was granted and voluntary consent was obtained. The athlete suffered a non-contact ACL tear that required surgical reconstruction. After surgery, a standard rehabilitation protocol was followed. Sixteen weeks post-surgery, the athlete resumed running activities, beginning with jogging and progressing to moderate and high speed running. Data were collected during training sessions conducted between 23 and 25 weeks post-surgery. Data collection was identical to that described in our companion paper (1). In short, running speeds were determined using a trunk-mounted GPS device (STATSports APEX). Accelerations near the foot were recorded via two ankle worn accelerometers (IMeasureU Blue Trident). After each session, data were downloaded and analyzed using the manufacturers' software packages (STATSports APEX, IMeasureU Step).

Five training sessions were examined. All sessions were conducted on an artificial turf field and the athlete wore running shoes. For each session, the athlete performed a series of repeated running bouts (90-110m). She was instructed to run at 25-40% (low), 60-70% (moderate) and 80-90% (high) of maximal effort; however, speed was self-selected. Four control (Control A-D) sessions were separated by one to two recovery days. On these days, low speed efforts were alternated with either a moderate or high speed run. The fifth session (Fatigue) consisted of repeated low speed running only. It was held the day following a relatively high training load session. It consisted of a series of repeated high speed runs (shuttles) at varying distances.

The specific sessions selected for analysis all involved running bouts of similar distances (~100m) with no directional changes within a bout. The sessions differed only in the bout speeds and number of bouts. The number of bouts during each session varied from 10 to 32 for a total of 100 individual bouts. Total distances covered each day ranged from 1231 to 3397m (Table 1). Data collection intervals began when the athlete initiated each bout and was stopped at the end of the deceleration phase.

Athlete readiness was determined using a counter movement, vertical jump (CMJ) test prior to each session. Three jumps were performed with the hands placed on the hips. Flight time and jump high was determined from the accelerometer of the trunk-mounted APEX unit (3). Briefly, vertical acceleration was integrated to obtain velocity. Take off and touch down times were determined at the peak positive and negative velocities. Flight time (FT) was computed as the difference and CMJ height calculated as ⅛ · g · FT2, where g is acceleration due to gravity. Preliminary work showed that this approach is a valid and reliable measure of CMJ. This was accomplished using a custom built device that allowed the APEX units to be projected vertically (in a manner similar to a CMJ) and determining displacement using high-speed video. These displacements compared favorably to those measured via the FT calculation (root mean square error was < 1%).

Descriptive statistics were computed and effects sizes (ES) were calculated using Cohen's D (small <0.2, medium= 0.2-0.8, large = >0.8). Also, non-linear regression was used to fit relationships between average impact load, total steps and running speed.

Results

Table 1 shows performance and training load data for all five sessions. For the four Control days, CMJ heights were similar (mean difference <0.12 cm) (Table 1). CMJ height was lower on the Fatigue day, suggesting reduced neuromuscular status compared to the previous session. Values for the load variable represent the total for the session and reflect the different combinations of bout speeds uses each day.

For individual bouts, here was a strong relationship between average impact load and average running speed (Figure 1, left). Based on visual inspection of the data, an exponential model was used to describe this relationship (r2 = 0.943). As running speed increased, the total steps during the bout decreased (r2 = 0.949).

Table 1. Performance and training load data for each of the five training sessions.

Variable	Control A	Control B	Control C	Control D	Fatigue
CMJ Height (cm)	27.32	26.98	27.06	27.13	24.82
Total Bouts (n)	30	32	10	14	12
Total Distance (m)	2748.3	3397.1	1039.4	1269.7	1231.2
Average Speed (km/hr)	11.55	12.00	14.57	14.33	6.81
Peak Speed (km/hr)	24.59	27.11	24.88	21.53	12.36
Total Impact Load (*g*)	30,292.3	41,894.1	18,136.2	21,520.2	21,036.2
Average Impact Load (*g*)	14.97	18.04	23.52	23.73	10.94
IMU Step Balance (%)	-2.89	-3.87	-5.2	-8.86	-12.16

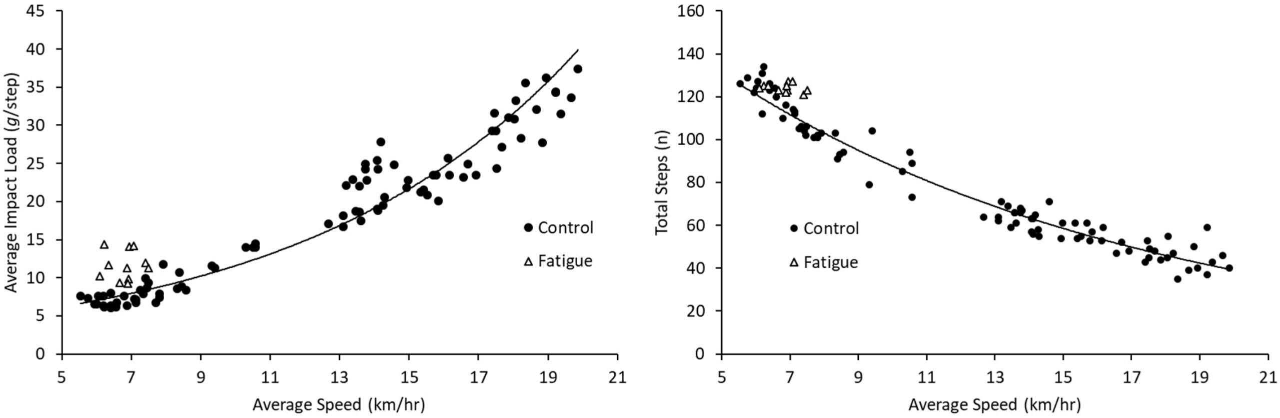

Figure 1. The relationships between IMeasureU average impact load (left) and total number of steps (right) versus APEX average running speed for all five days. Each point represents a single running bout (90-110m). The lines of best fit are based on an exponential relationship.

These relationships likely reflect a longer stride length with increasing speed and increased landing force at foot strike.

In this individual, right and left average impact loads varied somewhat differently as average speed of the bout increased (Figure 2). For the Control days, low running speeds (i.e. jogging) resulted average impact loadings that were fairly similar between limbs. However, as speed increased, loading on the left limb increased disproportionally to that of the right limb. At the high speeds, left impact load was clearly greater than that of the right limb. Table 2 shows mean values for the right and left average impact loads at the three self-selected running speeds for the Control and Fatigue days. As can be seen, the differences between right and left limbs increased with speed. Effect size for low speed running was small (Control days) and was large for moderate and high speed running. For the Fatigue day, when only low speed running was performed, left average impact loads were greater than the right (large ES).

Figure 3 shows the step balance values for all 100 running bouts. Step balance values become progressively more negative as speed increases, reflecting greater impact load being on the left limb than the right (see Figure 2). ES between self-selected speeds on the Control days were all large. Asymmetry during low speed running on the Fatigue day is greater than on the control days (large ES).

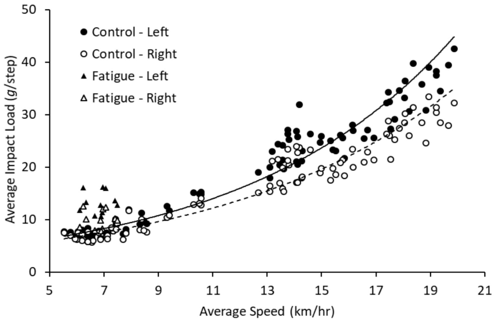

Figure 2. Right and left limb average impact loads versus running speed. The lines of best fit are based on an exponential equation.

Figure 2 also indicates that there is considerable variability in average running speed when the athlete was asked to run at the self-selected bout speeds. This is shown in Figure 4 where average speed within each self-selected bout are shown. There was some overlap in the actual speeds achieved during the moderate and high speed bouts. In some cases, average bout speed during a moderate pace running was greater that speeds during high speed running. For low, medium and high speed running, the coefficients of variation between bouts was 17.5, 11.2 and 11.6%, respectively, further indicating considerable variability in performance when this athlete was asked to self-pace her running.

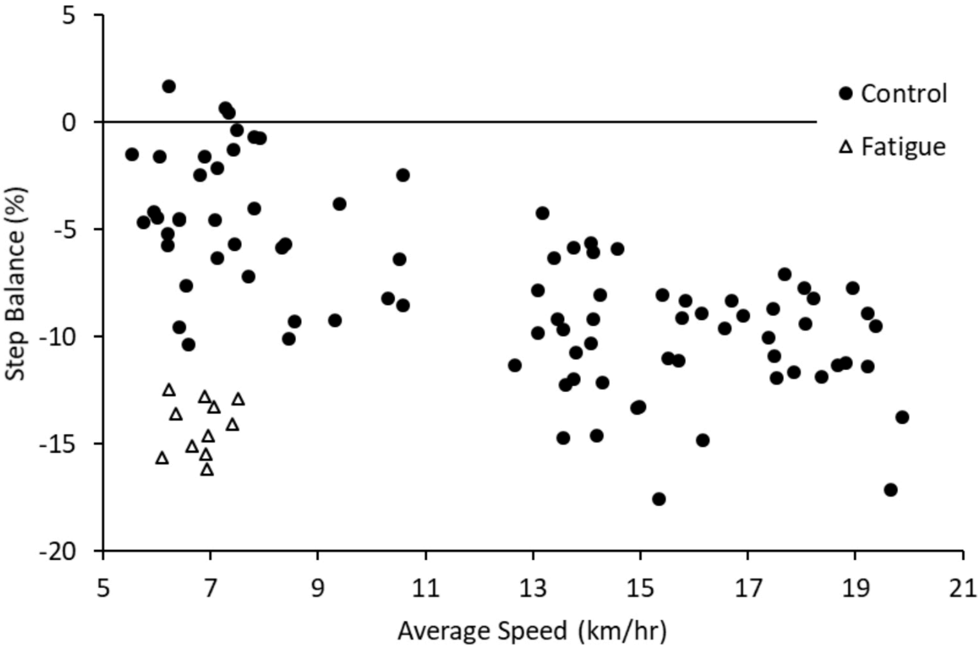

Figure 3. The relationship between IMeasureU step balance and running speeds for all days.

Table 2. Left and right average impact loads and step balance ($\bar{x} \pm SD$) as well as number of bouts for the three self-selected running speeds.

	Low	**Moderate**	**High**
Control (4 sessions)			
Left (g/step)	8.99 ± 2.66	25.13 ± 3.72	31.20 ± 6.10
Right (g/step)	8.16 ± 3.21	21.71 ± 3.40	25.07 ± 4.50
Step Balance (%)	-4.53 ± 3.26	-7.30 ± 3.30	-10.89 ± 2.17
Bouts (n)	37	28	23
Fatigue (1 session)			
Left (g/step)	12.27 ± 2.21		
Right (g/step)	9.61 ± 1.80[1]		
Step Balance (%)	-12.16 ± 1.24		
Bouts (n)	12		

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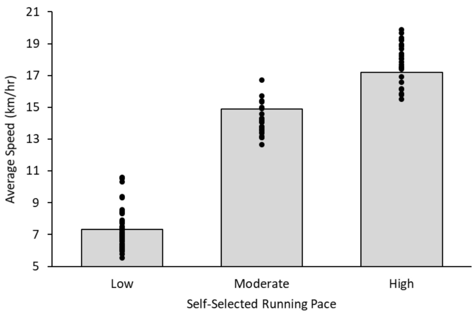

Figure 4. Variations in actual running speeds within each of the self-selected speed bouts. The circles represent each bout.

Discussion

Our results point out three key considerations for interpreting gait symmetry data. First, in an athlete recovering from ACL reconstruction, gait symmetry varies as a function of running speed. Second, long-term fatigue or lack of readiness can lead to increased gait asymmetry. Based on this, we suggest the need to provide comprehensive monitoring of an injured athlete, possibly including multiple monitoring tools and both accelerometry and GPS devices.

Table 1 shows asymmetry increasing from control sessions A to D, suggesting that symmetry worsened as the rehabilitation program progressed. However, average speed of the bouts within these sessions also increased. This emphasizes the need to monitor running speed in the injured athlete and compare that to the IMU step balance values. Otherwise misleading evaluation of athlete progress during rehabilitation could occur. Based on this study, tightly running speeds should be controlled or monitored in order to properly evaluate changes in IMU step balance data.

There are multiple reasons why step balance increases with running speed during ACL reconstruction recovery. Central mechanisms include kinesiophobia and a hesitancy of the athlete to maximally exercise the injured limb (4, 5). Pain and discomfort could cause one to lessen the impact on the injured limb. In our discussions with the athlete, she indicated on Control days that she was confident in running at high speeds and felt no pain or discomfort in the injured knee. On the other hand, neuromuscular mechanisms such weakness in both limbs and/or strength imbalance between limbs could alter gait (6, 7, 8). A strength deficit in the injured limb would likely be manifest at higher running speeds where greater concentric and eccentric contraction forces of the quadriceps, hamstring and calf muscles. In this athlete strength measurements indicate that she had not yet returned to pre-injury strength levels and had strength deficits in the injured limb (data not shown).

On the Fatigue day, the athlete noted that she was pain free but felt “tired” and her legs felt “dead”. Her vertical jump height was reduced by 8.5% compared to the control days, suggesting she was experiencing lingering effects of the previous days’ session. As with increasing running speeds, the large negative step balance during jogging on this day could arise from either central mechanisms (e.g. kinesiophobia) or neuromuscular strength deficits. Greater fatigue-induced force loss in the injured limb could lead to asymmetry (9). However, Webster et al., (10) found decreased asymmetry following fatiguing squatting exercise in ACL reconstructed patients. Unfortunately, our CMJ data could not determine if the injured leg exhibited greater force reduction compared to the healthy leg.

The precise mechanisms underlying gait asymmetry associated with fatigue and changes in running speed in the rehabilitating ACL injured patient remain to be seen. However, our results indicate that it is important to monitor running speed as well as the athlete's level of fatigue when interpreting metrics such as step balance. This can best be done by combining measurements provided by different technologies. In this example, the use of GPS and trunk accelerometry provide quantitative data regarding running speed and CMJ height. Whereas accelerometry at the ankle provides estimates of gait symmetry (11).

Practical Applications

This study shows the usefulness of field evaluations of running gait via wearable technology. It demonstrates the advantage of combining complementary measures of gait such as running speed and gait symmetry in this athlete. By measuring speed, a clearer picture in gait symmetry emerges. In this case, asymmetry increased with speed and under a fatigued condition. Also, actual running speed of this athlete varied considerably within each self-selected bout and there was some overlap in speeds between moderate and high speed efforts. This further emphasizes the importance of monitoring running speed when assessing gait symmetry using self-selected running speeds.

Limitations

Noteworthy limitation to this study include:

- As this is a case study of a single individual, the results are limited to a single athlete, with data collected during a time-frame small within the rehabilitation program. Given the variable nature of ACL injuries and rehabilitation progression, generalizing the results to the larger populations of injured and healthy athletes should be done with caution.
- These data represent a sample of convenience. That is, each session was designed by the strength and conditioning and sport medicine staffs, not the investigators.
- The data presented here reflect variables obtained from the STATSports APEX and IMeasureU Step platforms. Many of their calculations are proprietary and algorithms may differ from other manufacturers.

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