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Research

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Development of a Regression Model for the Treadmill Ground Reaction Force Components

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ABSTRACT

Treadmills allow for collecting multiple steps in a small area, and continuous testing for a long period of time with multiple speeds. These factors prove to be useful for biomechanics research laboratories that are usually equipped with floor embedded platforms. Acquiring instrumented treadmills with a built in force plate(s) – may not be financially feasible for many general purpose biomechanics laboratories; additionally instrumented treadmills only measures the vertical component of ground reaction force. The purpose of this study was to examine the components of Ground Reaction Force (GRF) in treadmill walking which were measured by placing a treadmill over floor-mounted force plates and to develop a set of regression equations to be used in associating treadmill's GRF components with GRF components obtained during overground walking. The GRF measured during the treadmill walk was compared to GRF measured in overground walking. A total of twelve male subjects participated in this study. The analysis of the data did not reveal statistical differences in the anterior-posterior component of the GRF (APGRFP1 and APGRFP2) and in the early-stance and mid-stance peaks of the vertical GRF (VGRFP1 and VGRFP2) between treadmill and overground walking. Statistical differences between treadmill and overground walking were found during late-stance for vertical ground reaction force (VGRFP3) and medial lateral ground reaction force (MLGRFP2) ($p<0.05$). During push-off- occurring in late-stance-vertical ground reaction force peaks (VGRFP3) were less in treadmill walking than in overground walking by 5-6% ($p<0.05$). The Medial-lateral ground reaction forces peaks (MLGRFP2) were also less in treadmill walking than in overground walking by 1-2% ($p<0.05$). In addition, five regression equations were developed for treadmill's GRF.

KEY WORDS: Biomechanics; Regression analysis.

ABBREVIATIONS: GRF: Ground Reaction Force; GLM: General Linear Model; CoP: Center of Pressure.

INTRODUCTION

Gait is defined as the arrangement in which limbs move during locomotion. Standing, walking and running properly involve a sequence of complex actions; during which bodies integrate sensory feedback from several systems of the body to properly control and coordinate muscles to prevent falling. Gait analysis is a descriptive tool that can help show how the systems of the body contribute to the way one stands, walks or runs and can help determine underlying problems.

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Gait analysis allow for frame by frame observation of motion, kinetics and kinematics enabling further insights into joints and the motion created. During gait analysis joint motion, electromyographic activity of the muscles, and the forces both created by and acting upon the body during human locomotion can be precisely recorded, measured and evaluated. Also, these measurements may be coordinated in time giving researchers and physicians the ability to compare between modes of evaluation (such as the walking on a treadmill *versus* overground walking), and thereby recommendations creating an accurate assessment of a person's ambulatory ability. This quantitative method utilizes motion capture systems, electromyography, and force platforms to identify gait abnormalities, after which a treatment can be recommended.

The utilization of treadmills in biomechanics laboratories that are typically equipped with floor mounted force plates can be beneficial. Treadmills uses a small area allowing for a large volume of steps to be achieved, and walking speed to be controlled. However, acquiring instrumented treadmills with a built in force plate(s) – may not be financially feasible for many general purpose biomechanics laboratories; additionally some instrumented treadmills only measure the vertical component of GRF.

A number of studies were conducted to investigate the overground and treadmill walking. Belli, et al.[1] validated a newly designed treadmill ergometer which measures vertical and horizontal GRFs during walking. Li and Hamill,[2] examined the vertical force component when approaching the gait transition point. Also, Dierick, et al.[3] developed an instrumented treadmill from a commercially available treadmill with 3D strain gauge force transducers. Lake and Robinson,[4] compared walking kinematics in two shoe conditions in overground and treadmill walking. Riley, et al.[5] showed that measures of GRF using instrumented treadmills are adequate for inverse dynamics analysis.

Goldberg, et al.[6] tested whether or not there would be any difference in the generation of anterior/posterior propulsion during treadmill and overground walking. Riley, et al.[7] evaluated and compared kinematics and kinetic parameters for treadmill running and overground running. Sohn, et al.[8] compared treadmill walking and overground walking at the same condition. Fellin, et al.[9] compared the variability of treadmill and overground running through a 3D lower limb kinematic analysis.

The purpose of this study was to examine a method by which the components of Ground Reaction Force (GRF) are measured through placing a treadmill (Kistler's Gaitway 9801A© Instrumented Treadmill) over four floor-mounted force plates. The GRF measured during the treadmill walk was compared to GRF measured in overground walking. The second objective of the study was use a regression approach to examine the association of GRF components during treadmill walking with measurements that can be obtained from the subject overground walk.

Methods

Subjects and Procedures

Twelve male college students aged 18 to 37, who indicated in a survey that they do not have any history of musculoskeletal injuries, were recruited. The subjects' age, height, and weight were (Mean ± Standard Deviation) 20.6±5.2years, 176.53±10.17cm, and 81.08±17.28 kg, respectively. Table 1 details the demographic data of the subjects.

Subject No.	Age (years)	Height (cm)	Weight (kg)	Average Walking Speed (km/hr)
1	19	180.3	72.6	4.5
2	37	165.7	86.6	3.4
3	20	190.5	98.9	3.1
4	19	185.4	82.8	3.2
5	18	165.1	61.7	2.7
6	20	171.5	69.2	3.7
7	18	166.4	55.3	4.2
8	20	165.1	74.4	2.9
9	18	183.5	78.9	3.0
10	20	193.0	120.7	3.4
11	19	179.1	83.0	4.0
12	19	172.7	88.9	3.8

Table 1: Demographic Data of Participating Subjects.

In accordance with the University of Miami Institutional Review Board's, all participants were briefed in advance about the experimental procedure of the study, and each signed a written consent form in the beginning of the experiment.

The University of Miami, Biomechanics Laboratory is equipped with four Kistler force plates: three Type 9281CA, and one Type 9287BA. Figure 1 shows the two arrangements of the force plates used in this study: overground walking and treadmill walking configurations.

The Biomechanics Laboratory utilizes a motion analysis technology by Oxford Metrics Group called Vicon Motion Capture System (www.vicon.com). It supports 64 channels of analog data and integrates and synchronizes ten infrared cameras and four force plates. A Kistler's Gaitway© Instrumented treadmill, Type 9810AS10 was utilized in this study. It measures the vertical force (F_Z) component, and the Center of Pressure (CoP) for complete consecutive foot strikes during walking and running. The treadmill uses a patented tandem force plate design and a patented algorithm to distinguish left and right foot strikes. The treadmill is accompanied by data collection software, Gaitway (Version 2.06, build 2013). In this study the Gaitway software was used only to distinguish the dominant foot strike of each subject. Subjects were first asked to walk at their normal speed across the floor-mounted force plates. Both the walking speed and GRF components were collected. The subject then was asked to walk on the treadmill that is placed over the floor-mounted force plates. Each of the four treadmill legs was cen-

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tred on a floor-mounted force plate. The treadmill speed was set to the subject's average speed recorded by Vicon during the overground walking trials. Force data were collected by the instrumented treadmill as well as by the four floor-mounted force plates. Vertical force component, (F_Z) was measured by both the instrumented treadmill and floor-mounted force plates. The floor-mounted force plates captured both the anterior/posterior (F_{AP}) and medial/lateral (F_{ML}) force components. Then the three components of the ground reactions forces, GRF, measured during a treadmill walk were compared with the three components of GRF measured during overground walking.

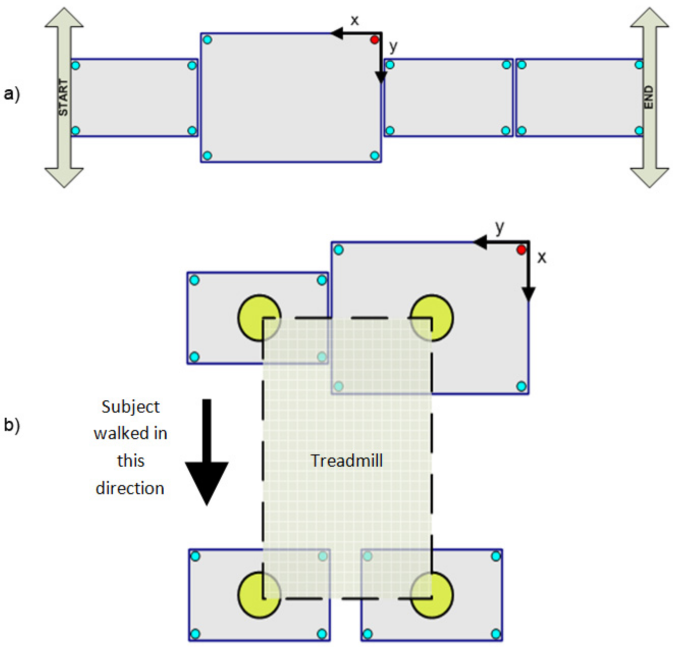

Figure 1: a) Overground force plates arrangement and b) Treadmill force plate's arrangement.

Overground Walking

Subjects were asked to walk barefooted through the Biomechanics Laboratory at their comfortable (normal) walking speed over floor mounted force plates (Figure 1A). Six randomly selected good trials were used in data analysis (a trial is considered "good" if the subject landed only one foot strike per force plate). Average walking speed for each subject was calculated using the time recorded by Vicon from the six selected trials.

Treadmill Walking

Before the subject's treadmill walking trials were conducted, the force plates were rearranged (Figure 1B). Our proposed method positions the Kistler's Gaitway Instrumented treadmill on top of the floor-mounted force plates such that each of the treadmill's legs was centered on a single force plate. Subjects were asked to practice walking on the treadmill barefooted since they walked barefooted over the Laboratory's ground and the treadmill's speed was set to the subject's average walking speed. Data was then collected from the floor-mounted force plates for a complete gait cycle. Data was recorded using Gaitway software and the Vicon Motion Capture System.

Treadmill GRF Components Regression Equations

The developed equations were used in an effort to provide biomechanics research laboratories with a tool to associate the different ground reaction force components with overground measurements for subjects walking over a treadmill without the need to acquire a more sophisticated treadmill equipped with force plates.

Terms studied for inclusion in the developed equations were: overground GRF, subject's Height (H) and Weight (W), walking speed (S), Stride length (SrLength), Stride time (SrTime), Step length (SpLength), Step time (SpTime), and the point of the gait cycle terminal contact-foot off-occur (FO). The treadmill GRF regression equations were constructed first by developing a correlation matrix between each of the treadmill GRF component and all of the parameters of interest to determine which of these parameters to include in the each predictive equation.

These regression equations may be of use to any biomechanics research laboratory equipped with only two force plates and any commercial treadmill. The subject would first walk across the two force plate once to obtain his overground GRF. Then the subject's weight and height as well as the overground reaction force components and the other gait parameters (walking speed, stride length, stride time, step time, step length, and foot off) would be implemented in the treadmill GRF regression equations to associate the treadmill GRF with these measurements.

RESULTS

Ground Reaction Forces

The pattern and amplitude of force-time curves for all components of ground reaction force obtained during treadmill walking were similar to data obtained during overground walking (Figure 2). In both treadmill walking and overground walking we can observe an increased absolute forces response during loading for VGRF (P1), MLGRF (P1), and APGRF (P1) and through push off for VGRF (P3), MLGRF (P2), and APGRF (P2). Also, minimal forces below body weight are apparent during mid-stance for VGRF (P2). These similarities indicate that acceleration patterns are alike during the stance phase of the gait cycle.[10-11]

General Linear Model (GLM) for Repeated Measures

GLM Repeated Measures is a statistical procedure used to model dependent variables measured at multiple times using analysis of variance. It tests the main effects on repeated measures of between-subjects (grouping) factors, the main effects of within-subjects factors such as measurement times, interaction

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effects between factors, covariate effects, and effects of interactions between covariates and between-subjects factors. Table 2 summarizes the results obtained from the GLM for repeated measures analysis.

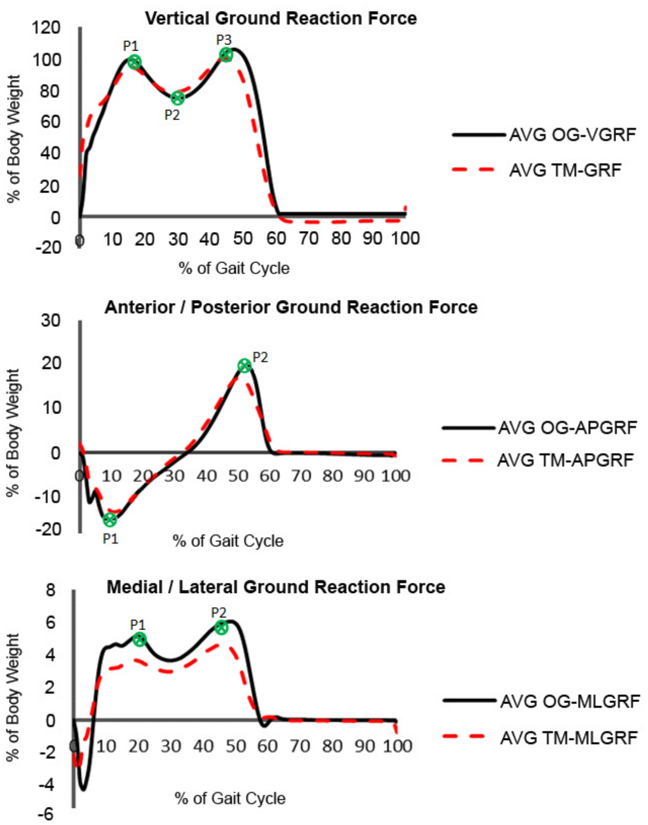

Figure 2: Force-time curves for all ground reaction force components during overground and treadmill walking.

Response Variable	Walk Type	Subject*Walk Interaction
VGRFP1	p = 0.780	p = 0.013*
VGRFP2	p = 0.061**	p = 0.000*
VGRFP3	p = 0.000*	p = 0.000*
APGRFP1	p = 0.090**	p = 0.000*
APGRFP2	p = 0.4662	p = 0.000*
MLGRFP1	p = 0.139	p = 0.245
MLGRFP2	p = 0.000*	p = 0.000*

*Significant at p=0.05
**Significant at p=0.10

Table 2: Results obtained from GLM for repeated measures.

The GLM for repeated measures suggests that at p=0.05, the third peak of F_Z and the second peak of F_{ML} significantly differ between treadmill walking and overground walking. At a higher p value (p=0.10), the analysis suggests that the second peak of F_Z (p=0.61) and the first peak of F_{AP} (p=0.09) also significantly differ between treadmill walking and overground walking. The higher p-value is considered here due to small sample size. In addition, the analysis reveals that the interaction between subjects and each walk (Subject Walk) is statistically significant for all response variables except for the first peak of F_{ML}.

The results of the GLM Repeated Measures model indicate that the overground walking observations were significantly different from the treadmill walking observations for some of the measurement types, but not others. Specifically, at p=0.05, the third peak of the vertical ground reaction force and the second peak of the medial-lateral ground reaction force were significantly different in overground gait from treadmill gait. The model also indicated that the Subject/Walk Type interaction was significantly different at the p=0.05 level for all response variables but one: first peak of medial-lateral ground reaction force (MLGRFP1).

The analysis of the data did not reveal statistical differences in the anterior-posterior component of the GRF (APGRFP1 and APGRFP2) and in the early-stance and mid-stance peaks of the vertical GRF (VGRFP1 and VGRFP2) between treadmill and overground walking. Our findings are in agreement with the literature.[5,12] Kram, et al.[12] constructed a force treadmill to measure and record vertical, horizontal and lateral components of the GRFs (F_z, F_y and F_x, respectively) and moments (M_z, M_y and M_x, respectively) exerted by walking and running humans. Riley, et al.[5] evaluated and compared kinematic (body segment orientations and joint angles) and kinetic (net joint moments and joint powers) parameters for treadmill running and overground running. Both studies found that anterior-posterior and vertical components of the GRF in treadmill and overground locomotion to be very similar.

Statistical differences between treadmill and overground walking were found during late-stance for vertical ground reaction force (VGRFP3) and medial lateral ground reaction force (MLGRFP2) ($p<0.05$). During push-off-occurring in late-stance-vertical ground reaction force peaks (VGRFP3) were less in treadmill walking than in overground walking by 5-6%. The medial-lateral ground reaction forces peaks (MLGRFP2) were also less in treadmill walking than in overground walking by 1-2%. The force peaks during push-off are related to the extension of support limb during late-stance. Not extending limb fully would result in a shorter stride length.

Several authors have reported decreased stride length as one of the differences between treadmill and overground walking. Stolz, et al.[13] noted that step frequency increased by 7% in adults and by 10% in children while stride length and stance phase decreased during treadmill walking in comparison to overground walking. Alton, et al.[14] reported that stance phase was shortened significantly in treadmill walking when human locomotion was analyzed on the treadmill and on the ground for identical walking speed. Others also reported similar variability of steps and several kinematic measurements.[15-17] The reported decreased stride length in treadmill walking in these studies supports our outcomes of decreased force peaks during push-off.

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Another explanation for the reduced peaks of ground reaction force in late stance would be the effect of treadmill belt speed fluctuations on the subject. Braking (shear) forces are at maximum during limb loading in early stance and frictional forces increase, as a result the belt speed slows down causing the subject to exert negative work on the treadmill. White et al.[11] warned that "the potential for lower push-off forces should be considered when interpreting treadmill locomotion particularly for higher speeds and for heavier individuals since belt friction forces will increase with body mass". van Ingen Schenau,[18] indicated that it is required for the belt speed of the treadmill to be constant to obtain similarity between treadmill and overground gait. Savelberg, et al.[19] observed a 5% decrease in belt speed in the braking phase in high-power treadmill.

Because further insight into this interaction was needed, main effects plots and interaction plots (Figure 3) were generated to be analyzed alongside scatterplots of response variable *versus* subject. In these plots, Walk 1 represented the average of six overground walks while Walk 2 represented one treadmill walk. The goal was to investigate whether or not the presence of the subject-walk interaction influenced results.[20]

In examining the main effects plots (Figures 3), the interactions plots, and the scatterplots of response variable *versus* subject, it is seen that overground walking (Walk 1) has higher response variables values for some subjects, and treadmill walking (Walk 2) has higher response variables values for others. Hence, the presence of an interaction doesn't influence the results in the Walk Type column of Table 2 (the results obtained from GLM for repeated measures). In examining the values of the Walk Type column of Table 2, GLM for repeated measures indicate that for VGRFP1, VGRFP2, APGRFP1, APGRFP2 and MLGRFP1, there is no overall statistically detectable differences between the two walking styles at p=0.05. However, that much variability exists among the subjects must be noted.

Main effects plots and interaction plots for each peak in the components of GRF as well as scatter plots of response variable *versus* subject were used to study if the existence of this interaction swayed the results. Although high variability among the subjects exists, and subject/walk type interaction is statistically significant, the plots suggest that the presence of such interaction did not influence the results in the walk type. In other words, the inter subject variability did not influence whether the overground gait is significantly different from treadmill gait or not. Since the small sample size might restrict the power of analysis to detect differences even if they exist then we should note that the results of the GLM for repeated measures test are suggestive of existence of statistical differences that did not meet the threshold of p=0.05 statistical significance between overground gait and treadmill gait in the second peak of the vertical ground reaction force (VGRFP2) and the first peak of the anterior-posterior ground reaction force (APGRFP1).

Treadmill GRF Components Regression Equations

A total of five treadmill GRF regression equations were developed. The treadmill GRF components were: VGRFP1_TM, VGRFP2_TM, VGRFP3_TM, APGRFP1_TM, and MLGRFP1_TM. The terms included in each equation were based mainly on the correlation between each term and the corresponding treadmill GRF component. The developed equations are shown below (equations 1-5).

$$VGRFP1\_TM = -11.2 + 1.11 VGRFP1\_OG \quad (\text{adjusted-}R^2 = 75.9\%) \quad (1)$$

$$VGRFP2\_TM = -49.2 + 2.23 FO \quad (\text{adjusted-}R^2 = 37.5\%) \quad (2)$$

$$VGRFP3\_TM = 142 + 0.363 VGRFP3\_OG - 140\, SpTime \quad (\text{adjusted-}R^2 = 59.9\%) \quad (3)$$

$$APGRFP1\_TM = 113 - 1.25 FO - 47.7\, SpLength \quad (\text{adjusted-}R^2 = 29.6\%) \quad (4)$$

$$MLGRFP1\_TM = -11.6 + 0.292 FO \quad (\text{adjusted-}R^2 = 40.1\%) \quad (5)$$

(*FO*: foot off, *SpTime*: step time, and *SpLength*: step length)

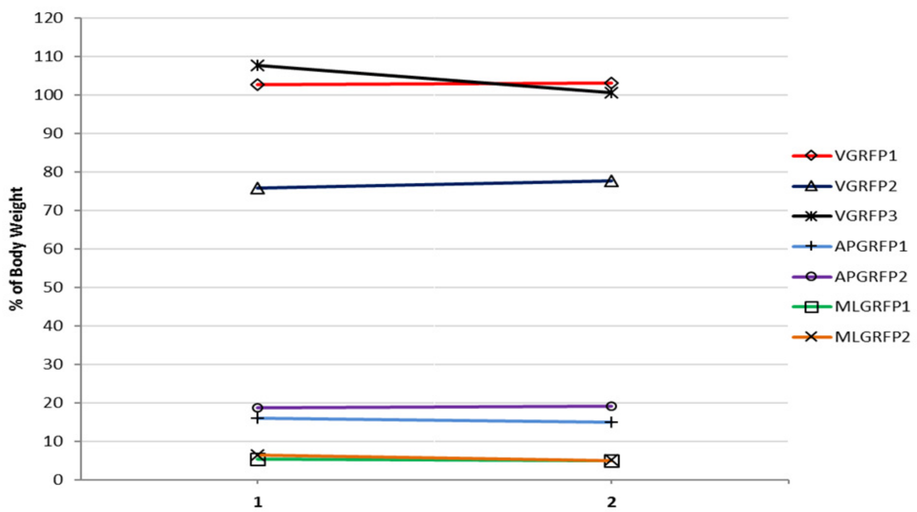

Figure 3: Main effects plots for GRF components.

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CONCLUSIONS

The aim of this research was to examine a method by which components of GRFs are measured by placing a treadmill on top of four floor mounted force platforms. The use of treadmills has always been popular in physical rehabilitation centers, and it is becoming increasingly more common in gait laboratories. Such laboratories are typically equipped with floor embedded force platform(s) allowing the analysis of only one or two consecutive steps. Treadmills allow for the collection of multiple consecutive steps in a small space, and the ability to study walking patterns over a prolonged period of time. Collecting forces exerted during locomotion allows for kinetic analyses during treadmill ambulation. However, acquiring instrumented treadmills with a built in force plate(s) may not be financially feasible for many general purpose biomechanics laboratories; additionally many instrumented treadmills only measure the vertical component of GRF.

The second objective of the study was to develop a set of regression equations for a subject walking on a non-instrumented treadmill based on the subject's gait parameters while walking on floor embedded force plates. Five equations were developed to estimate associations between components of GRF in treadmill walking and various measurements which can be obtained during an overground walking trial. The equations can be used for Vertical Ground Reaction Force Peak 1 (VGRFP1), Vertical Ground Reaction Force Peak 2 (VGRFP2), Vertical Ground Reaction Force Peak 3 (VGRFP3), Anterior-Posterior Ground Reaction Force Peak 1 (APGRFP1), and Medial-Lateral Ground Reaction Force Peak 1 (MLGRFP1) for treadmill walking.

CONFLICTS OF INTERERST: None.

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Research

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Effect of a 6 Week Plyometric Training Program on Agility, Vertical Jump Height and Peak Torque Ratio of Indian Taekwondo Players

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ABSTRACT

Purpose: Taekwondo demands for quick change in direction while keeping balance, strength, speed and body control through high level of lower limb strength, agility to improve performance.
Methodology: 30 elite national level male Taekwondo players (mean age 22.0±1.6 years; mean Height, 174.4±4.4; mean mass 62.4±6.9 kg, training experience were 21±2.29 years, 5±1.70 years respectively) were divided into two groups, G1 (n=15) has undergone plyometric training for 6 weeks and G2 (n=15) control group. Before and before after 6 weeks all subjects underwent for Illinois agility test, vertical jump by kinematic measurement system t and isotonic muscles (Hamstrings - quadriceps) peak torque ratio by isokinetic dynamometer.
Result: After 6 week of plyometric training program agility, vertical jump height and peak torque ratio was improved significantly ($p<0.05$) in G1 group (plyometric training group). No significant changes found in G2 group (control group).
Conclusion: Improvement in agility, vertical jump and peak torque ratio of taekwondo players occur after 6 week of plyometric training which will reducing the risk of lower limb injuries.

KEYWORDS: Taekwondo; Plyometric Training; Agility Test; Vertical Jump; Peak Torque Ratio.

INTRODUCTION

The word "Taekwondo" is derived from the Korean word "Tae" means "to kick"; "Kwon" implies "punching" and "Do" means "method." Thus taekwondo is the technique of self defence that involves the skilful application of techniques that include punching; jumping kicks, blocks, actions with hands and feet. Taekwondo is a form of martial art that has evolved by combining many different styles of martial arts that existed in Korea.

Plyometrics are training techniques used by athletes in all types of sports to increase strength and explosiveness.[1] Plyometrics consists of a rapid stretching of a muscle (eccentric action) immediately followed by a concentric or shortening action of the same muscle and connective tissue.[2] Researchers have shown that plyometric training, when used with a periodized strength-training program, can contribute to improvements in vertical jump performance, acceleration, leg strength, muscular power, increased joint awareness, and overall proprioception.[3]

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Agility is the ability to maintain or control body position while quickly changing direction during a series of movements.[4] Agility training is thought to be a re-enforcement of motor programming through neuromuscular conditioning and neural adaptation of muscle spindle, Golgi-tendon organs, and joint proprioceptors.[5-7] Performance is often dependent upon the athlete's jumping ability during offensive and defensive skills.[8]

Jump performances appears to be contingent on the quantity and efficiency in which force is produced at the hip, knee and ankle joints, explosive strength of the legs and hips should result in a higher vertical jump.

The most common sports in which one's vertical jump is measured are track and field, basketball, football and volley ball, taekwondo. Although plyometric training has been shown to increase performance variables, little scientific information is available to determine the effect of plyometric training on taekwondo players and if plyometric training actually enhances agility, vertical jump height and peak torque ratio in taekwondo players. Therefore, the purpose of this study was to determine the effect of a 6-week plyometric training program on agility, vertical jump height and peak torque ratio of Indian taekwondo players.

METHODOLOGY

30 elite national level male Taekwondo players (Based on these findings, the Indian taekwondo athletes were shown significant improvement in agility, vertical jump height and peak torque ratio in dominant and non-dominant leg after 6 weeks of plyometric training. age, training experience were 21±2.29 years, 5±1.70 years respectively) gave their informed consent to serve as subjects in the study. The procedure, benefits, and potential risks of study were explained to the participants before signing the informed consent form and starting the test. The study was approved by the Institutional Ethics Committee of Faculty of Sports Medicine and Physiotherapy, Guru Nanak Dev University, Amritsar.

Inclusion criteria included that subjects agreed with the purpose of this study, subject with musculoskeletal problems such as lower limb fracture and sprain/strain, existing neurologic problems as well as respiratory or cardiovascular system problems were excluded.[9]

The subjects of the study were randomly divided into two groups: a control group (n 15), a plyometric exercises group (n 15). All subjects agreed not to change or increase their current exercise habits during the course of the study. The plyometric exercises group participated in a 6-week exercises program performing a variety of plyometric exercises designed for the lower extremity (Table 1), while the control group did not participate in any plyometric exercises. Participant were tested pre and post the 6 week training period. Before testing, participants performed a 5- minute warm-up protocol consisting of submaximal running and active stretching. Kinematic Measurement System (Fitness technology, Australia) , Isokinetic Dynamometer (60°/sec) and Illinois test was used to measure the vertical jump height , peak torque ratio and agility. All dependent variables were entered into Statistical Package for Social Sciences (SPSS Inc., Chicago, Ill) 17 version.`

Training Week	Training volume (foot contacts)	Plyometric Drill	Sets × Reps	Training Intensity
Week 1 (3 days per week; an alternate day)	90 (2-3 min rest intervals)	Side to side ankle hops	2 × 15	Low
		Standing jump and reach	2 × 15	Low
		Front Cone Hops	5 × 16	Low
Week 2 (3 days per week; an alternate day)	120 (2-3 min rest intervals)	Side to Side ankle hops	2 × 15	Low
		Standing long Jump	5 × 6	Low
		Lateral jump over barrier	2 ×15	Medium
		Double leg hops	5 × 6	Medium
Week 3 (3 days per week; an alternate day)	120 (2-3 min rest intervals)	Side to Side ankle hops	2 × 12	Low
		Standing long jump	4 × 6	Low
		Lateral jump over barrier	2 × 12	Medium
		Double leg hops	3 × 8	Medium
		Lateral cone hops	2 × 12	Medium

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Week 4 (3 days per week; an alternate day)	140 (2-3 min rest intervals)	Diagonal cone hops	4 × 8	Low
		Standing long jump with lateral sprint	4 × 8	Medium
		Lateral cone hops	2 × 12	Medium
		Single leg bounding	4 × 7	High
		Lateral jump single leg	4 × 6	High
Week 5 (3 days per week; an alternate day)	140 (2-3 min rest intervals)	Diagonal cone hops	2 × 7	Low
		Standing long jump with lateral sprint	4 × 7	Medium
		Lateral cone hops	4 × 7	Medium
		Cone hops with 180 degree turn	4 × 7	Medium
		Single leg bounding	4 × 7	High
		Lateral jump single leg	2 × 7	High
Week 6 (3 days per week; an alternate day)	120 (2-3 min rest intervals)	Diagonal cone hops	2 × 12	Low
		Hexagon drill	2 × 12	Low
		Cone hops with change of direction sprint	4 × 6	Medium
		Double leg hops	3 × 8	Medium
		Lateral jump single leg	4 × 6	High

Table 1: Plyometric 6-week training protocol.

RESULT

In agility test experimental group shows six no improvement in agility after 6 week of plyometric training as well as in control group. (Table 2)

Agility Test (sec)	Control Group	Experimental Group
Illinois Test	Pre-Test (sec)	Post –Test
Mean±SD	17.13 ± 0.41	17.13 ± 0.42
Mean±SD	17.18 ±0.48	17.12 ±0.47

Table 2: Comparison of Agility (sec) pre and post training in Experimental and Control group.

In Vertical Jump test experimental group shows significant improvement in height after 6 week of plyometric training ($p<0.00$) whereas control group shows non significant result. (Table 3)

Vertical Jump (m)	Control Group	Experimental Group
	Pre –Test	Post-Test
Mean±SD	0.36 ±0.06	0.36 ± 0.05
Mean±SD	0.37 ± 0.05	0.40 ± 0.06
P VALUE	0.36	<0.00
T VALUE	0.359	3.67

Table 3: Comparison of Vertical Jump Height (m) pre and post training protocol in Experimental and Control group.

In isokinetic dynamometer (peak torque force) dominant and non- dominant Leg of Control Group shows non significant improvement but in plyometric group dominant leg and non dominant leg shows significant improvement ($p<0.01$), ($p<0.00$). (Table 4)

DISCUSSION

Present study indicated that 6 weeks of plyometric training was able to increase peak torque ratio, agility, vertical jump height in Indian taekwondo players.

Peak torque force of dominant and non- dominant leg of plyometric group shows significant improvement ($p<0.01$), ($p<0.00$). Generation of absolute anaerobic power output depend directly on the amount of muscle mass, especially the thigh muscle cross-sectional area. Moreover, factor influencing maximal peak anaerobic power achieved by individual rely on present of the amount of type II muscle fibers.[9] Peak anaerobic power reflects short-term anaerobic performance and mean anaerobic power reflects intermediate-term performance.[10] Factors determining the anaerobic performance include morphological (muscle architecture and fiber type), physiological (efficiency of metabolic pathway), biochemical (substrate availability and accumulation of reaction products) and neuromotor (motor skill and motor unit recruitment) variables. Regular participation in a plyometric training program can improve measures of strength and power in adults.[11]

In present study, subjects who underwent in to plyometric training were no improvement in agility. Therefore, we were not found a positive relationship between plyometric training and improvements in agility test. In a previous study of plyometric training, the authors' reported that improvements were a result of enhanced motor unit recruitment patters.[7] Neural adaptation usually occurs when athletes respond or react as a result of improved coordination between the CNS signal and

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ISOKINETIC DYNAMOMETER (PEAK TORQUE FORCE)	CONTROL GROUP				PLYOMETRIC GROUP			
	DL		NDL		DL		NDL	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST
MEAN±SD	0.55 ± 0.11	0.56 ± 0.09	0.56 ± 0.11	0.55 ± 0.11	0.71 ± 0.12	0.73 ± 0.13	0.68 ± 0.09	0.70 ± 0.09
P VALUE	<0.27		<0.21		<0.01		<0.00	
T VALUE	0.61		0.80		2.41		3.36	

Table 4: Comparison of Peak Torque force pre and post training protocol in Dominant and Non-Dominant leg in Experimental and Control group.

proprioceptive feedback.[6] However, in present we could not determine if neural adaptations occurred *via* synchronous firing of the motor neurons or better facilitation of neural impulses to the spinal cord which also supports the suggestions of Potteiger et al.[7] Therefore, more studies are needed to determine neural adaptations as a result of plyometric training and how it affects agility. In present study there was no improvement in agility performance.

In case of vertical jump there was significant improvement found in Plyometric training group in present study. Vertical jump performance, acceleration, leg strength muscle power, increased joint awareness and overall proprioception enhanced by plyometrics.[12]

This is in agreement with some studies which applied resistance training or soccer specific strength training programs and found increased ball speed during the kick so in taekwondo also there is need of increase power of lower leg and kick should be forceful therefore the present study will shows that the 6 weeks of plyometric training and resistance training both shows the significant improvement in agility vertical jump and peak torque force.

CONCLUSION

Based on findings of this study, the Indian taekwondo athletes were shown significant improvement in agility, vertical jump height and peak torque ratio in dominant and non-dominant leg after 6 weeks of plyometric training which was very encouraging and demonstrate the benefits plyometric training can have on performance. Use of plyometrics can improve strength and explosiveness while working to become more agile. In addition, our results support that improvements in agility can occur in as little as 6 weeks of plyometric training which can be useful during the last preparatory phase before in-season competition for athletes. We recommended coaches and trainers to apply these training protocol to improve performance.

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STATEMENTS

Contributorship

Jaspal Singh Sandhu provided the set-up for the study. Amrinder Singh planned the study and submitted the study. Avinash Kumar Boyat conducted the study.

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The set-up was organized by the Department of Sports Medicine and Physiotherapy, Guru Nanak Dev University Amritsar, Punjab (India) and there was no funding issues.

Competing interests

There was no conflict of interests.

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Case Report

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Functional Movement Analysis in the Differential Diagnosis of a Patient with a Posterolateral Corner Knee Injury

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ABSTRACT

Study Design: Resident's case study.
Background and Purpose: Functional Movement Analysis (FMA) including observational gait analysis are powerful tools that can be used to guide patient examination and differential diagnosis process.
Case description: An 18-year-old female was referred to physical therapy with a diagnosis of gait abnormality and a chief complaint of left medial knee and left medial hip pain. Two orthopedic surgeons suspected neurologic pathology due to inconclusive findings on physical examination, an abnormal antalgic gait pattern, and negative findings on Magnetic Resonance Imaging (MRI) and radiographic studies. The physical therapist gathered a comprehensive subjective history, and performed a functional movement analysis including observational gait analysis. The findings were used to guide a full musculoskeletal examination. Correlating the functional movement analysis with subjective history and comprehensive musculoskeletal examination, the therapist found the patient to have subtle but definite lateral knee joint laxity. This was hypothesized to be driving the abnormal gait pattern and causing her hip and knee pain.
Outcomes: Stress radiographs, suggested by the physical therapist, were ordered and confirmed the therapist's finding of lateral knee instability. The patient subsequently had surgery to repair and augment her popliteal fibular ligament and lateral collateral ligament. She underwent postoperative physical therapy, and returned to her prior level of function with full resolution of her gait deviations and pain.
Discussion: Functional movement analysis is a powerful and unique tool that clinicians can use when evaluating and treating patients.
Level of Evidence: Therapy, level 4.

KEYWORDS: Functional Movement Assessment (FMA); Observational gait analysis; Posterolateral corner; Knee pain.

ABBREVIATIONS: MRI: Magnetic Resonance Imaging; FMA: Functional Movement Analysis; PLC: Posterior Lateral Corner; LCL: Lateral Collateral Ligament; PMT: Popliteus Muscle Tendon; PFL: Popliteal Fibular Ligament.

BACKGROUND AND PURPOSE

The structures of the Posterior Lateral Corner (PLC) are responsible for posterolateral stabilization of the knee. The PLC is made up of the Lateral Collateral Ligament (LCL), Popliteus Muscle Tendon (PMT), and the Popliteal Fibular Ligament (PFL). PLC injuries can be a

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diagnostic challenge, especially in the presence of concurrent cruciate ligament injuries, which account for 87% of all cases.[1,2] Recent findings suggest that undiagnosed PLC injuries can be particularly detrimental, potentially leading to further injury of the knee. Magnetic Resonance Imaging (MRI) is considered the gold standard for diagnosing ligamentous injuries in the knee, with an accuracy of 95% for identifying major injury to the PLC structures.[3] While MRI can be extremely helpful in diagnosing acute PLC injuries, they have been found to be less accurate in diagnosing chronic tears, and are costly.[4] Therefore, a thorough history and physical examination should always precede MRI and guide the interpretation of diagnostic imaging results.[2]

A typical physical examination consists of visual observation, palpation, and range of motion, along with special testing for structural integrity. This information tells the diagnostician little about function. Currently, there is limited research on the diagnostic benefits of utilizing Functional Movement Analysis (FMA) and its role in the diagnostic process. This case report describes a false negative MRI and physical examination from two board certified orthopedic surgeons, which then required a systematic and thorough investigation of history, mechanism, and functional movement analysis by the physical therapist, leading to a non-traditional series of images to establish an accurate diagnosis.

CASE DESCRIPTION

Patient History and Systems Review

An 18-year-old Caucasian female soccer player was referred for physical therapy by an orthopedic surgeon with a diagnosis of "gait abnormality, left lower extremity." Significant to this patient's history is an eight-year history of Type I Diabetes and four surgeries on her contralateral right knee beginning with an Anterior Cruciate Ligament (ACL) reconstruction 2 years prior to this incident.

The patient presented to an orthopedic knee surgeon with a one-week history of left medial knee and groin pain and an abnormal acquired gait. Plain film radiographs and Magnetic Resonance Imaging (MRI) of the knee were ordered. Results were negative for bony or soft tissue abnormalities. As a result of the uncharacteristic abnormal gait pattern, lack of significant objective findings on physical examination, and negative findings on imaging studies, she was referred to another board certified orthopedic knee surgeon for a second opinion.

The second orthopedic surgeon performed a comprehensive physical examination, which included special testing for ligamentous instability. Full-length bilateral weight-bearing radiographs were ordered to assess bony mal-alignment as a possible cause for the abnormal gait pattern. These films were negative for pathology. Strength, Range of Motion (ROM), and special testing for ligamentous instability and meniscal injury were all unremarkable. Due to the uncommon gait presentation, along with negative findings on MRI and radiograph, the orthopedic surgeon suspected a neurologic lesion such as Multiple Sclerosis (MS) or peripheral neuropathy. She was referred to Neurology for an Electromyographic (EMG) study of bilateral lower extremities to rule out peripheral neuropathy. MRI studies of the cervical spine to the sacrum were ordered to evaluate for cord lesions. MRI of the brain was ordered to rule out brain lesions. MRI of the hip was also ordered to rule out intra-articular hip pathology as she was complaining of medial hip pain. Before all imaging and diagnostic studies were completed, the patient was referred to and evaluated by the physical therapist. A chronological history of events following the injury are detailed in Table 1.

Week 1	• Visits orthopedic surgeon #1 • (-) Knee radiographs and magnetic resonance imaging (MRI) • Referred to orthopedic surgeon #2
Week 2	• Visits orthopedic surgeon #2 • (-) Radiographs • Bilateral lower extremity electromyography (EMG) study ordered • MRI of cervical spine (C/S), thoracic spine (T/S), lumbar spine (L/S), and sacral spine ordered • Physical therapy referral given
Week 3-4	• (-) Bilateral lower extremity EMG study ordered • (-) MRI of C/S, T/S, L/S, and sacrum • Brain and hip MRI ordered
Week 5	• Patient evaluated by physical therapist • Treating physical therapist suggests stress radiographs be taken to rule out lateral collateral ligament (LCL) strain • (-) Brain MRI
Week 6	• (+) Stress radiographs bilaterally for increased varus gapping
3 months	• Arthroscopic reconstruction of LCL, posterior fibular ligament and posterior corner

Table 1: Chronological history of events after injury.

Examination

The initial evaluation was approximately five weeks after the patient's injury. A thorough subjective history was collected from the patient, including all events surrounding the current injury, as well as a detailed past medical history (Table 2).

Gestation	Cyst in utero, resolved spontaneously
2 years	Fractured clavicle, fell off bench
9 years	Running backwards, fractured wrist
10 years	Diagnosed with diabetes type 1 (insulin pump)
15 years	Fractured big toe playing soccer
16 years	Nov 2009 anterior cruciate ligament and meniscus surgery
17 years	June 2010 scar tissue debridement
18 years	Dec 2010 scar tissue debridement and anterior cruciate ligament debridement, Jan 2011 developed reflex sympathetic dystrophy, had negative bone scan, had nerve block with no relief
18 years	Feb 2011 Endo button removal and scar tissue debridement
18 years	April 7, 2011 doing kickboxing video, kicked high in air, felt awkward, then planted and felt immediate pain, next day felt laxity, and walking digressed.

Table 2: Past medical history.

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The initial mechanism of injury occurred when the patient was performing an exercise-video kickboxing regimen that called for her to do a high lateral kick in the air with her left lower extremity followed by a lateral lunge with the same extremity. She felt an awkward and unfamiliar sensation on the left lateral knee during the kick. Upon landing in a lateral lunge position with the left hip and knee flexed, she felt an immediate sharp pain in her knee. The patient recalled having a slight feeling of instability in the knee joint when walking the next day. There was a slow increase of perceived instability in the subsequent five weeks, which developed into medial knee pain and medial hip and groin pain. The patient's self-reported outcome measure score on intake for the Lower Extremity Functional Scale was a 13/80 with an 80/80 being no disability.[5]

Significant past medical history included insulin dependent Type I Diabetes. Also of note was her right knee surgical history. Approximately 2 years prior to her current injury, she tore her right Anterior Cruciate Ligament (ACL) and meniscus. She had surgery to reconstruct the ligament and debride the meniscus. Six months post-repair, scar tissue debridement and release was performed secondary to knee arthrofibrosis and significant pain.[6] Due to ongoing stiffness and pain she had a second arthroscopic release. She subsequently developed reflex sympathetic dystrophy six months later. She received a bone scan, which was negative for fracture, infection, and malignancy. She underwent femoral nerve block with no relief. Her retained hardware for her ACL reconstruction (Endobutton, Smith & Nephew, Andover, MA, USA) was removed and scar tissue was debrided again the following month. This was two months prior to the current injury. With injuries and surgery taking place on the right knee, the differential diagnosis process was complicated by eliminating the reference limb, which a physical therapist would typically use for side-to-side comparisons.[7]

Following the subjective history, a detailed gait analysis was performed (see http://openventio.org/Volume1_Issue2/SEMOJ-1-108/videos.php For online video links). At initial contact/loading response with the involved limb, the patient landed with heel strike, and did not achieve the normal 5-15 degrees of knee flexion used for shock absorption. During mid-stance, the knee collapsed to approximately 35 degrees of flexion. During the collapse there was a rapid frontal plane deviation of a varus thrust which quickly reversed into a valgus thrust with associated femoral internal rotation and adduction. There was no heel-off in terminal stance.

With the data gathered up to this point, preliminary hypotheses pertaining to pathoanatomic diagnoses were formulated, leading to a standardized gait analysis (Table 3).

The patient may have been avoiding the 15 degrees of knee flexion used for shock absorption during loading response in order to avoid the compressive forces at the patella associated with quadriceps contraction.[8,9] A meniscal tear could cause the tibiofemoral joint to lock in extension during swing.[9] A meniscal tear could also lead to decreased joint congruency, which decreases stability.[10] Ligamentous laxity or a tear would also lead to decreased stability of the joint.[9] A common compensation to improve joint stability is to fully extend the knee. Locking the knee in full extension makes the joint more stable by increasing joint congruency. Also, using an active contraction of the quadriceps and hamstrings will increase compression of the tibiofemoral joint, which increases the joint's surface friction and makes any movement in the joint more difficult.[9] Full extension also allows the posterior capsule to provide posterior stability while keeping the knee joint away from the flexion torque that is present as soon as the knee becomes even slightly flexed.[8,9] The valgus thrust and collapse of the knee into 35 degrees of flexion could have been secondary to pain mediated weakness of gluteus medius, maximus and/or the quadriceps. The valgus thrust seen in mid-stance may have been an over-compensatory response to avoid feeling lateral instability following the initial varus thrust.[9]

Following a standard gait analysis, further functional movement analysis was used to accentuate body structure impairments. Lateral stepping to the left reproduced a feeling of instability, but was not reproduced in lateral stepping to the right. Toe-walking and heel-walking was performed in full knee extension without significant impairment or deviation of the knee in the frontal plane. The patient did not demonstrate any significant deviations or symptom reproduction during backward walking. She was able to transfer her weight from toe to heel, but did not achieve full knee extension. She also demonstrated a shorter stride length on the left *versus* the right. The patient was able to

Initial Contact Loading Response	Demonstrates decreased knee flexion for shock absorption. The knee then collapses and there is a rapid frontal plane deviation of femoral abduction which quickly reverses itself into femoral adduction and internal rotation.
Mid-stance	Full knee extension is not achieved. The femur remains in internal rotation and adduction.
Terminal stance	No heel-off.
Swing Phases	No significant findings.
Toe-walking	Able to lock out knee without noticeable impairments.
Heel-walking	Able to lock out knee without noticeable impairments.
Lateral side-stepping	A feeling of instability is reported on the lateral portion of her knee when she is side-stepping toward the left. No instability noted during side-stepping to the right.
Backwards walking	Demonstrates backwards walking without significant deviation. The patient is able to go from toe to heel, but does not get into full knee extension. Stride length is shortened on the left versus the right.

Table 3: Detailed gait analysis.

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balance for greater than 30 seconds on a single limb, bilaterally. The patient did, however, demonstrate left lateral knee instability in static standing; while in static standing the patient swayed her knees side to side, and demonstrated a larger-than-normal varus angulation and excursion to the left, which was significantly greater than the right. The patient had associated feeling of awkward sensitivity and instability.

Considering the patient's story, location of pain and findings from the FMA, a rupture or insufficiency of the lateral collateral ligament complex and Posterolateral corner (PLC) was suspected. Patients with neurologic pathology commonly present with motor control impairments affecting balance, backwards walking and gait. This patient was able to demonstrate most of these functional movements without difficulty, ruling down the likelihood of neurologic pathology.[11-13] However, pathologies such as multiple sclerosis, demyelinating polyneuropathy or any pathology that could affect joint proprioception could not be ruled out before a formal assessment of the peripheral and central nervous system. With the data gathered during the FMA, the therapist proceeded with an objective table examination to rule up or down the most likely diagnoses on the differential diagnosis list.

Babinski and Hoffman's were normal and patellar and Achilles reflexes were 2^+ bilaterally. Knee active and passive ROM was approximately 0-135º bilaterally. Strength testing revealed deficits on the left for knee flexion, and hip flexion, extension, and abduction. There was associated pain with hip and knee flexion. See Table 4 for a full overview of strength testing results.

Muscle	Right	Left
Hip Flexion	5	4+*
Knee extension	5	5
Knee flexion	5	4*
Dorsiflexion	5	5
Great toe extension	5	5
Plantar flexion	5	5 (25 heel raises with knee locked)
Side-lying hip abduction	4+	4-
Hip extension	4+	4

*denotes pain

Table 4: Manual muscle test grades at initial evaluation.

Knee special tests revealed positive laxity with apprehension and an audible click with Varus Stress Testing on the left.[14] The Dial-Test, which tests for PLC, with or without concurrent PCL injury, was positive at 30 degrees of flexion and negative at 90 degrees of flexion. This is indicative of a PLC injury without PCL involvement.[15,16] Also noted was increased laxity but solid end-feel with Anterior Drawer and Lachman's on the left.[17-19] Pivot-shift, McMurray's, Apley's Compression, Thessaly's and Valgus Stress Testing were negative.[17-20]

Hip special tests were then performed. The FABER test revealed a distance of 13 cm lateral patella to the table on left versus 8 cm on the right.[21] This finding can be indicative of decreased muscle length in a number of different muscles that flex, adduct and/or internally rotate the femur. It can also indicate decreased anterior hip capsule mobility.[22] This test, however, is not considered positive for intra-articular pathology without the presence of pain.[21] FADIR, which places the hip in end range flexion, adduction and internal rotation, and a hip scour test were both negative, ruling down the likelihood of an ace tabular labral tear.[21,23] See Table 5 for a full overview of special testing findings for the left knee and hip.

Special Tests for the knee	
Varus Stress	+*
Dial Test	+
Valgus Stress	-
Anterior Drawer	- (2+ laxity, but solid end feel noted)
Lachman's	- (2+ laxity, but solid end feel noted)
Pivot Shift	-
McMurray's	-
Apley's Compression	-
Thessaly's	-
Special Tests for the hip	
FABER	- (negative for pain, but mobility/flexibility deficit note)
FADIR	-
Hip Scour	-

*denotes pain

Table 5: Special testing.

Following the physical therapy evaluation, the therapist felt confident that lateral instability was causing the abnormal gait pattern. The varus to valgus thrust seen in mid-stance was postulated to be a protective compensation to limit varus force to the lateral structures of the knee. The medial hip and knee pain were a direct result of the compensatory abnormal gait pattern. Other major physical examination findings that supported this hypothesis included the following: a mechanism of injury that was caused by a lateral force to the knee, no apparent abnormality in toe/heel/backwards walking, normal neurologic reflexes, and a positive Dial and a positive Varus-Stress Test.

With the provisional hypothesis of knee lateral instability, and considering negative findings of ligamentous injury on MRI, the physical therapist recommended stress radiographs be performed to rule out capsuloligamentous insufficiency, and referred the patient back to the orthopedic surgeon for stress radiographs. Stress radiographs are not typically ordered in standard orthopedic practice. Radiographs with varus and valgus stress were completed. Varus stress radiographs demonstrated excessive lateral joint-line gapping, both in the knee extended and knee flexed positions. These findings confirmed the physical therapist's hypothesis of lateral ligamentous insufficiency.[24,25] The patient opted to undergo surgery to repair and augment with reconstruction of the lateral structures contributing to the structural instability (Figure 1).

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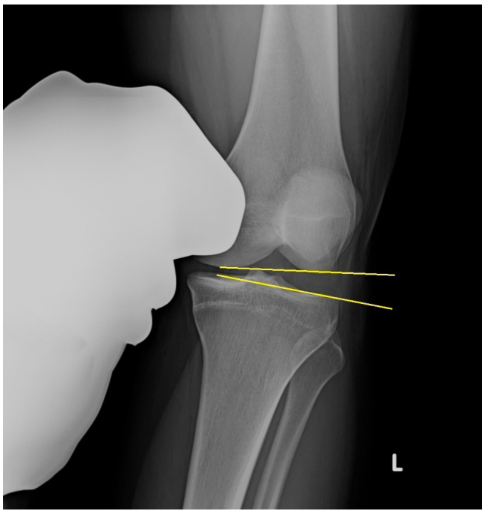

Radiograph with varus stress applied in knee flexion, revealing lateral joint line laxity.

Figure 1: Stress radiographs left knee.

Intervention

In preparation for surgery, the patient was seen for two pre-operative visits by the physical therapist. Treatment focused on proximal hip and knee strengthening and neuromuscular re-education to control frontal plan deviations during the loading response and mid-stance phases of gait, and ultimately to correct her compensatory abnormal gait pattern. Treatment was also aided by the use of a SERF strap, which is a flexible strap designed to help stabilize the femur in external rotation during dynamic activities.[26] This strap has been shown to control excessive femoral internal rotation as well as increase the muscular activation of the gluteus medius.

Intraoperatively, the surgeon discovered excessive laxity of both the Lateral Collateral Ligament (LCL) and the PLC, or more specifically, the Popliteal Fibular Ligament (PFL) and popliteus tendon. These ligaments along with the posterior capsule were described as being "patulous" or frayed. The LCL, PFL and popliteus tendon were reconstructed using allografts and were then sutured to the patient's native LCL, PFL and popliteus tendon. The post-surgery protocol called for strict non-weight bearing for six weeks to minimize load on the LCL. Post-operative physical therapy was started after four weeks after surgery. The patient underwent physical therapy for six months, and returned to running without restrictions. Post-operative physical therapy consisted of active and passive range of motion, neuromuscular re-education, both open and closed kinetic-chain strengthening, and functional movement training to return the patient to a high level of exercise and running.

DISCUSSION

The patient's gait demonstrated an abnormal varus thrust during loading response that was not seen on the contralateral limb. This was immediately followed by valgus collapse during the mid-stance phase of gait. This gait deviation may indicate that the lateral knee structures, specifically the LCL, could be compromised. Injury to the LCL is the least common of all knee ligament injuries with an incidence of 4%. Injury to the LCL usually occurs as a soft-tissue avulsion off the proximal attachment on the femur or as a bone avulsion associated with an arcuate fracture of the fibular head.[3,27] LCL injuries usually are part of more extensive injuries that involve the PLC.[27] The LCL attaches to the femur approximately equidistant from the posterior and distal borders of the lateral femoral condyle and distally to a superior and laterally facing V-shaped plateau on the head of the fibula.[28] It is the main structure responsible for resisting varus stress, particularly in the initial 0° to 30° of knee flexion, and limits external rotation of a flexed knee.[29,30]

Posterolateral corner injuries account for 16% of all knee ligament injuries and often occur in combination with other ligament injuries.[31-33] Most common mechanisms of injury include: a blow to the anteromedial aspect of the knee when the joint is in or near full extension; contact and noncontact hyperextension injuries; a valgus contact force applied to a flexed knee; or extreme tibial external rotation with the knee in flexion or hyperextension.[30,31] The three most important stabilizing structures of the posterolateral knee are the PFL, popliteus tendon, and fibular collateral ligament.[34] Their main role is to prevent excessive knee varus, tibial external rotation and posterolateral rotation.[35,36] Though it is unclear from the description of the original injury, this patient may have injured her PLC, PFL and popliteus tendon with a similar knee varus and tibial external rotation overload, either from the lateral kick or the lateral lunge. Patients who have suffered an injury to their posterolateral corner commonly present with altered gait mechanics, however a recognizable pattern has not yet been reported. In this and other clinicians' experiences, a varus force at the knee can commonly be seen during the loading response to mid-stance phases of gait.[3] The patient may then fully contract the quadriceps to lock out the knee in hyperextension in order to create additional stability through the passive intact posterior knee structures and compression of the tibiofemoral joint.[30] As seen with the patient presented in this case study, it is also possible that they will over-correct a varus thrust using a compensatory valgus thrust during the phases of loading response to mid-stance. This pattern allows for support by medial passive and active structures such as the medial collateral ligament, semimembranosus, semitendinosus, sartorius and gracilis.[30]

It is important to note that while a standard physical examination with special testing for structural integrity is vital to the evaluation process; functional movement analysis can significantly affect the differential diagnosis. In this case study, the functional movement and gait analysis helped guide the clinician to request appropriate imaging and ultimately lead to a correct diagnosis, which was confirmed intraoperatively.[37-39]

CONCLUSION

In this case study, a very systematic approach to col-

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lecting subjective information led to functional movement tests and table examination that revealed findings contrary to the orthopedists' impression and imaging results. These findings were used to help guide clinical reasoning and ultimately confirm the hypothesis of lateral instability.

While there is more discussion about the use of functional movement analysis, the literature is sparse defining how and when it should be implemented. It is a powerful and unique tool physical therapists can use in evaluating and treating patients. The findings should always be correlated with subjective information, objective tests and measures, and be confirmed by imaging when possible. More research should be done to demonstrate the role of functional movement analysis, and how it can best be implemented to determine a patient's diagnosis and treatment plan.

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CONFLICTS OF INTEREST

The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the manuscript.

CONSENT

For the videos shown in the practise, we have obtained the consent statement from the girl who was involved in this case study.

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Opinion

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Using the Placebo Effect to Isolate Control Mechanisms of Athletic Performance: A Research Protocol

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ABSTRACT

Placebo effects are common in all areas of medicine and beyond and thus, are also present when ergogenic aids are used to enhance performance in athletes. While they usually are regarded as secondary and a nuisance in relation to performance-improving nutritional supplements, we here propose to utilize them to investigate central control mechanisms of athletic performance. Following a brief review of the current literature on placebo effects in sports, we outline a research protocol designed to understand the neurobiological basis of endurance performance, limiting factors and the integration of central and peripheral fatigue mechanisms. A placebo response to ergogenic aids will be elicited to isolate and study both central and peripheral components of performance regulation. This protocol employs endurance performance measurements, electroencephalography, functional near-infrared spectroscopy and ratings of perceived exertion in order to quantify the performance altering placebo response elicited by a nutritional ergogenic aid. A model is proposed integrating the placebo response with current theories of performance determining and limiting factors such as the central governor model and the central fatigue hypothesis. The first experiment is concerned with the influence of the mode of administration of an ergogenic aid on endurance performance. In the second experiment, the cortical processes underlying increased motor performance will be investigated using electroencephalography. The third experiment will employ functional near-infrared spectroscopy to look at the integration of cortico-muscular feed forward and feedback signaling pathways mediating fatigue. This protocol provides an integrative approach for neuroscience and sports science research, investigating cortical processes involved in the placebo induced exploitation of residual central and peripheral resources causing better athletic performance. It also will affect prevention and treatment of diseases which may be caused by a lack of physical activity or which may cause a decrease in the ability to be physically active.

KEYWORDS: Endurance performance; Ergogenic aid; Placebo response; Central fatigue; EEG; fNIRS.

ABBREVIATIONS: 5-HT: Serotonin; BCAA: Branched Chain Amino Acids; BOLD: Blood-Oxygenation-Level-Dependent; CF: Central Fatigue; CFH: Central Fatigue Hypothesis; CGM: Central Governor Model; CHO: Carbohydrates; CNS: Central Nervous System; deoxy-Hb: deoxygenated hemoglobin; EEG: Electroencephalography; FA: Fatty Acids; fNIRS: functional Near-infrared spectroscopy; Hb: Hemoglobin; HR: Heart Rate; O_2: Oxygen; RPE: Rating of Perceived Exertion (subjective effort ratings); Trp: Tryptophan; VO_2: Oxygen Consumption.

BACKGROUND

Athletic Performance

The most commonly considered factors, which determine physical performance, are

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of peripheral nature: muscle strength and cardio-respiratory capacity. These are influenced largely by genetic factors and by specific training. However, it is unlikely that these factors alone decide the outcome of a sporting competition with often only milliseconds or one point between a first and a second place. The determinants of athletic performance are complex and thus must involve top down control mechanisms regulating motor performance.

For decades the brain was not considered to play an important role in determining athletic performance. The original model of factors limiting human exercise performance was proposed by Hill in 1924 suggesting that performance declines when oxygen requirements of the exercising muscles exceed cardiac output capabilities and therefore have to function anaerobically, producing excess lactic acid, which in turn impairs muscle contractions.[1] This model states, that a disruption of homoeostasis is the cause of exercise termination. Although a decrease in voluntary muscular contractility plays a role in sports performance, this point is rarely reached during intense training and even competition, especially in the endurance domain.

Theories like Hill's "Catastrophe model" dominated the field of exercise and performance science for over half a century. Many exercise physiologists have noted early on, that exercise capacity is most likely limited by an integration of multiple factors. To reach the highest level of performance all systems have to be optimized, from muscles, lung and heart, all the way to the highest control-unit: the brain. If the brain as the central control system does not function appropriately, the remaining systems cannot perform at their best.

Today most exercise physiologists, athletes and coaches agree that performance decreases with increasing fatigue. The term fatigue is commonly split into two components: peripheral and central fatigue. While peripheral fatigue is broadly defined as a reduction of muscular force which is easily measurable, central fatigue is often described as a sensation or an emotion which is more difficult to quantify.[2] There is currently no consensus on a clear-cut definition of fatigue, however attempts of clarification have been made,[3] including – in the context of sports performance – the inability to meet a force expectation, which is the inability to generate maximal force or a slowdown in building up of force.[4]

Models of Fatigue

Different theories and models to explain fatigue in endurance sports currently exist and include the Central Governor Model (CGM),[5] critical body temperature[6] and the neurohumoral response also called Central Fatigue Hypothesis (CFH).[7] The CGM suggests the brain as a regulator of muscle performance, thus including factors like motivation, presence of competitors, knowledge of end point, deception and self-belief.[8] The anticipatory regulation of exercise performance is what distinguishes it from the CFH, which suggests that fatigue occurs as a result of changes in neurotransmitter concentration in the brain.[9] The most prevalent theory about the neurohumoral basis of Central Fatigue (CF) is the Trp-5-HT-hypothesis developed by Newsholme and others,[10] which is based on disturbances in brain serotonin (5-HT) levels.

Fatigue can be caused by processes anywhere along the brain-muscle pathway and viewing peripheral and central mechanisms as separate entities will not further our understanding of fatigue as a whole. Viewing the CGM and the CFH not as mutually exclusive, but rather as complementary may be the key to unravel the mechanism determining exercise performance.

Placebo Effect and Ergogenic Aids

An indicator for the important role of the brain in limiting or enhancing exercise performance is that it can be influenced by expectancy effects caused by beliefs about the efficacy of ergogenic aids.[11-13] An ergogenic aid is any form of mechanical, pharmacological, physiological, psychological or nutritional aid that enhances exercise performance. In the past decade several studies suggested a measurable placebo effect in exercise performance, which is not substance specific and is significantly influenced by factors such as personality of the athlete and perceptual characteristics of the ergogenic aid.[14] This has first been shown in the early 1970's in weight lifters, whose performance increased significantly when they were falsely told that they took anabolic steroids.[15] Results of such expectations and believes are commonly known as placebo effects and are defined as the improvement of symptoms due to the administration of an inert treatment.

The underlying neurobiological or psychophysiological change caused by a placebo manipulation is called *placebo response*. The placebo response can contribute to the efficacy of any active treatment[16] and can be triggered by the patients' expectations, the relationship to the physician/trainer or by behavioural conditioning.[17-20] The placebo effect is an empowering concept, because it provides a scientific basis for the influence of the psychosocial context on treatment outcomes and reveals how internal control processes shape perception, emotions and motivation and *vice versa*.[21]

Several studies have demonstrated that athletes who believed that they had ingested carbohydrates (CHO),[22] caffeine[23,24] or had used a respiratory training device[25] showed performance enhancement. A review of 12 studies looking at sports performance changes following interventions noted placebo responses between -7.8% and +50.7%.[26] In 2008, Pollo, et al. were able to show that placebo-induced expectations of better performance can reduce the perception of fatigue while increasing muscle work, suggesting top-down modulation of exercise performance *via* central fatigue mechanisms.[27] A recent study investigated elite athletes' attitudes toward placebo induced per-

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formance enhancement and concluded that roughly 50% of elite athletes have experienced placebo effects, the majority believes in the possible ergogenic effect of placebos and those with past placebo experiences would not mind them being more widely used.[28]

Studies of the placebo response of nutritional supplements have looked at specific isolated substances such as glucose,[29,30] amino acids,[31] caffeine,[32] alcohol[33] and ginseng.[34] By general definition, nutritional supplements are "[...] products that are taken orally with the intention to supplement the diet by increasing the total dietary intake of vitamins and minerals and non-vitamin non-mineral substances".[35] The placebo response evoked through the consumption of a nutritional supplement administered in the form of food, which stimulates a multitude of senses may, however, be proportionally larger due to increased stimulus salience. The association of physiological changes and specific flavours was shown in studies eliciting immune responses *via* classical flavour conditioning[36,37] and in studies influencing the severity of motion sickness *via* Pavlovian flavour conditioning.[38] A qualitative study with 267 undergraduate college students compared the perceived effectiveness in enhancing strength, endurance and concentration of nine fictive nutritional supplements differing in shape (e.g. drink, lotion, pill, capsule, bar, powder), colour (e.g. green, white, red) and mode of administration (drink, swallow, application to skin). The results showed that the perceptual characteristics of nutritional supplements influence the expectation of their consumers regarding their potency, however there seems to be large inter-individual variability.[39] The mode of administration of a CHO supplement was analyzed for its influence on the metabolic response and exercise performance and researchers found no difference in the beneficial effects of sport beans, sport drink or gel.[40] These results however could be due to a ceiling effect, meaning that the administered dose of CHO reached the level above which variance in endurance performance is no longer measurable, thus masking any potential influence of perceptual attributes. Including placebo groups receiving the same supplements matched for flavour and appearance without CHO could have revealed any potential differences.

Looking at nutritional supplements as ergogenic aids, in the context of exercise performance, provides a way to quantify the associated placebo response *via* both objective and subjective performance measures and thus provides access to the investigation of central control mechanisms of motor performance.

Neural Basis of Motor Performance

The neural basis of placebo induced performance changes have only recently been investigated in detail. Most knowledge so far has come from studies investigating the placebo effect in motor disorders such as Parkinson's disease.[41-43] However, Fiori and colleagues from the University of Verona recently published a study investigating changes in the cortico-spinal system during placebo induced motor performance enhancement.[44] They elicited increases in force production by generating expectations about the efficacy of transcutaneous electrical nerve stimulation and used transcranial magnetic stimulation to show, that this increase in force was caused by a rise in corticospinal excitability.

Electroencephalography (EEG)

EEG is a scientifically well-grounded method based on recording voltage fluctuations from multiple electrodes placed on the scalp (non-invasive). These voltage differences represent neural brain activity with millisecond precision. This high temporal resolution allows precise tracking of parameters such as attention, emotional engagement or wakefulness. Decades of EEG research provide a solid base of knowledge about the implications of the measured data. However, only few studies so far have used EEG to look at difference in neural processing between placebo and real treatments.[45-47]

Brain activity during endurance exercise has not been investigated much because of the difficulties involved in measuring cortical parameters in sport science. During exercise large movement artifacts arise, which can negatively affect EEG signal quality.

Standardized test conditions on a bicycle ergometer, can however minimize the influence of artifacts and enable the recording of cortical parameters during exercise.[48] To completely understand affective and perceptual responses during exercise and central fatigue mechanisms, it is crucial to understand the brain processes involved.[49-51] Studies have shown, that changes in brain activity occur secondary to the metabolic changes associated with central fatigue during prolonged exercise[52-54] and activity in the frontal cortex is associated with affective[55] and perceptual[49] responses to acute bouts of exercise.

Some research has been conducted on the brain level mechanisms underlying motor performance by comparing cortical activation patterns of individuals of different skill levels in specific complex sports related tasks. This is becoming a popular approach in the field of sports performance research and has been applied in disciplines such as rifle shooting,[56,57] golf,[58,59] karate[60] and archery.[61] However, only a handful of studies attempted the analysis of brain activity during endurance exercise so far. The studies which employed EEG unfortunately recorded from only few electrodes, thus limiting the informative value.[62,63] Already in 1985, Nybo and Nielsen recorded EEG during exercise at 60% VO_2 max in normal and hot ambient temperatures and found no changes in EEG at 18 ºC but an increase in the ratio of alpha to beta frequency at 40 °C. Unfortunately this study also recorded from only three electrode sites: left frontal, midline central and midline occipital.[49] A meta-analysis on EEG responses during and after exercise showed increases in alpha, delta, theta and

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beta activity during and following exercise. The authors argue that understanding EEG brain activity during experimental manipulations like fatigue requires EEG responses to exercise under normal controlled conditions to be understood first.[64] Bailey and colleagues examined multiple frequency bands from lateral (F7, F8, F3, F4), central (C3, C4) and parietal (P3, P4) sites during different intensities of aerobic exercise to volitional fatigue. They found global increases in theta, alpha and beta frequencies during exercise and suggest future studies to examine the association between changes in EEG and changes in cognition, emotions, and perception as well as the influence of peripheral physiology on EEG during exercise.[65]

Functional Near-Infrared Spectroscopy (fNIRS)

fNIRS is a functional neuroimaging method to measure brain activity through hemodynamic responses associated with neural activity. It is entirely non-invasive and is based on measuring Near-infrared (NIR) light attenuation and temporal or phasic changes.

Light in the NIR spectrum (700-900 nm) can pass unfiltered through skin, tissue, and bone, while being partially absorbed by Hemoglobin (Hb) and deoxygenated-hemoglobin (deoxy-Hb). It is the difference in the absorption spectra of deoxy-Hb and oxygenated Hb by which the relative changes in hemoglobin concentration is measured. fNIRS applies the principle of neuro-vascular coupling, known as the BOLD (Blood-Oxygenation-Level-Dependent) response. Neuronal activity is associated with changes in localized cerebral blood flow, but cannot measure cortical activity more than 4 cm deep and has limited spatial resolution.[66]

Interestingly, fNIRS is also becoming a widely used instrument for measuring muscle O_2 saturation and changes in muscle hemoglobin volume. Muscle O_2 saturation represents a dynamic balance between O_2 supply and O_2 consumption in small vessels. The role of NIRS in exercise physiology is increasing (nearly, 2004) and the results of several studies suggest that NIRS is a powerful tool for being applied successfully in sports medicine,[67] as NIRS can objectively evaluate muscle oxidative metabolism and its modifications following interventions.[68,69] The development of light wireless NIRS devices, operating on Bluetooth basis allow the application on freely moving subjects and enable the use during exercise protocols. Several studies have shown that these wireless NIRS devices produce nearly artifact free and reproducible data.[70]

fNIRS can measure changes in O_2 saturation both centrally on the level of the cortex and peripherally at the level of muscles. Further, it is portable and not easily susceptible to movement artifacts. It therefore seems to be the ideal tool to research the integration of central and peripheral fatigue processes and determinants of exercise performance.[71]

Rating of Perceived Exertion (RPE)

Perceptual effort ratings are a key compliment to objective performance measures in order to determine the degree of physical strain including information from the periphery (muscles, joints, cardiovascular, respiratory and central nervous system). The most commonly used scaling method to quantify subjective perception of effort in sports science is the Rating of Perceived Exertion (RPE) developed by Gunnar Borg in 1970.[72] It was constructed to increase linearly with exercise intensity on a cycle ergometer to fit with the linear increases in VO_2 and Heart Rate (HR) observed with increasing workload.

PROPOSED MODEL

This model integrates current theories of the neurobiological control mechanisms of exercise performance and central fatigue by employing the placebo response as a mean to isolate the central component of performance enhancement. An ergogenic aid may directly influence both central and peripheral fatigue mechanisms, while also eliciting a placebo response. This placebo response may in turn influence the central regulatory feed-forward signals through expectations as well as the perception of feedback signals from the periphery. The combination of all these factors then determines exercise performance (Figure 1).

METHODS AND DESIGN

Experiment 1

The first experiment is designed to investigate the acute ergogenic effect of branched chain amino acids (BCAA) on endurance performance. The focus will be on the role of the placebo effect in enhancing endurance performance and how this effect can be modified by the mode of supplement administration. To ensure all subjects have similar expectations of the supplement, they will receive information emphasizing the acute enhancing effects of BCAAs on endurance performance. Using BCAAs as a supplement is ideal, because endurance athletes have little or no experience with the acute effect of amino acids in contrast to abundant experience with CHOs. Using BCAAs as a supplement rather than CHO (which are classically used in endurance studies) thus makes it difficult for them to guess which study group they are in (placebo *vs.* supplement), ensuring a solid double-blind study design. BCAAs and their placebo counterparts will be given in either food (pudding) or supplement (capsule) form. Athletes are told that they have a 50% chance of receiving BCAAs. All information regarding the intervention will be given on paper and all athletes will be verbally instructed in a standardized fashion by the same experimenter.

The Ethics Committee of the University Hospital of Tübingen has given a positive vote on the ethics proposal on January 29th, 2014 and the project is registered as a Clinical Trial at the German Registry for Clinical Trials (DRKS, DRKS00005802).

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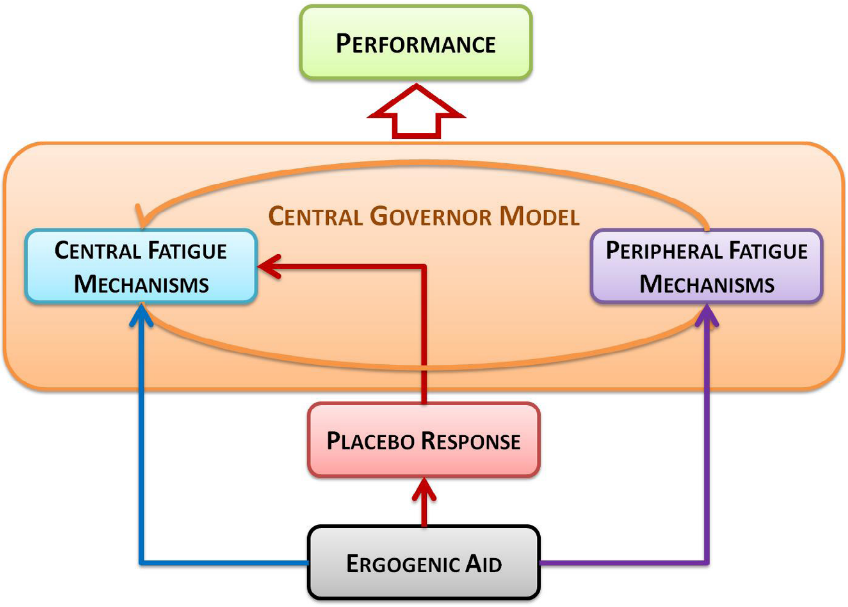

Figure 1: Schematic of the proposed model for the involvement of the placebo effect in athletic performance.

Hypotheses Experiment 1

The performance enhancing placebo response elicited by a nutritional ergogenic aid is larger when administered as food than as capsule. This is based on the assumption that stimulus salience (food>capsule) has a larger influence on the placebo response than stimulus conditioning (supplement>capsule). We thus hypothesize, that the food group will show a larger increase in performance between baseline time trial (TT_b) and intervention time trial (TT_i).

Methods Experiment 1

Using a 2(food *vs.* capsule) × 2(supplement *vs.* placebo) factorial analysis of variance with repeated measures with an effect size of 0.25, a power of 0.80 and alpha of 0.05, 30 athletes have to be included in the study (as calculated with the software G Power). Thus, 30 ambitious male bicyclists and triathletes between the age of 18 and 40 will be recruited fulfilling the following criteria: 3-5 bicycle training sessions per week during season and regular participation in competitions (mountain bike, triathlon, road racing). Exclusion criteria were serious illness, use of medication during the time of the study and training pause in the 4 weeks immediately prior to the study. Each participant will be measured on 4 days at the performance diagnostics laboratory at the Department of Sports Medicine in Tübingen, Germany.

A 2×2 randomized double-blind repeated measures design with a no-treatment control group will be used with the factors intervention (placebo *vs.* supplement) and form (food *vs.* capsule) and motor performance measures (objective and subjective) as dependent variables. Athletes will be randomly assigned to one of 5 groups: Food supplement (FS) (N=6), food placebo (FP) (N=6), capsule supplement (CS) (N=6), capsule placebo (CP) (N=6) or no-treatment control (C) (N=6). The no-treatment group controls for training and learning effects. All athletes are subjected to 4 test sessions. During the first visit they are provided with a detailed informed consent form. Once they consent to participate in the study, they undergo a thorough examination by an attending medical doctor, who then admits them to participate in the study. Once all formal requirements are met, a performance test is performed to assess current maximal aerobic capacity (VO_2 max), Lactate Threshold (LT) and Individual Anaerobic Threshold (IAT) using a stepwise test protocol (40 W/ 40 W/ 3 min) on a bicycle ergometer. This protocol begins at a work rate of 40 Watt increasing by 40 Watt at regular 3-minute intervals. The protocol goes on until subjects can no longer maintain cadence above 65 rpm or voluntarily stop due to exhaustion. At the end of each interval blood samples are taken from the right ear lobe to determine the lactate concentration at each workload. Simultaneously inhaled and exhaled air is measured *via* spiro-ergometry to determine oxygen consumption (VO_2), carbon dioxide production (VCO_2) and total ventilation (also called cardio pulmonary exercise test or CPET).

The next session serves as a test time trial (TT_t), where participants are familiarized with the isokinetic SRM bicycle ergometer (SRM GmbH) in a 45 min practice session consisting of 10 min warm-up, 30 min time trial (TT_p) and 5 min cool-down. The SRM is a practical tool to measure physical condition with predefined constant cadence (here: 95 rpm) and the cyclist himself determines his power output. This allows for an accurate measurement of endurance capacity in relation to a specific duration. At the end of this session, participants are expected to be familiar with the testing procedure.

During the third session the 45min baseline performance time trial (TT_b) takes place, during which the athletes are instructed to attempt to cycle for maximal average power output over time at a constant cadence of 95 rpm. The time trial is pre-

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ceded by a 10 min warm-up and followed by a 5 min cool-down at variable rpm and fixed work load (1.5* bodyweight in kg).

In the 4th session the intervention with the ergogenic supplement takes place (TT_i). TT_i is scheduled exactly 7 days later at the same time of day as TT_b (8 am or 10 am), in order to minimize influences of natural performance fluctuations. Thirty minutes prior to the time trial at TT_i athletes receive their respective intervention (FS, FP, CS, CP, C), depending on which experimental group they were assigned to. The athletes have to come fasted (12 h no food and caffeine) on both test days (TT_b and TT_i) to ensure equal absorption rates of the supplement and control for external variables such as performance influences of caffeine and CHOs.

During both TT_b and TT_i performance is measured along with physiological measurements before, during and after the test. During the trial, blood samples (20 µl) are collected from the ear lobe in 5 min intervals for lactate diagnostics and the pulse is measured *via* a chest strap heart rate sensor.

To control for potential covariates, athletes will also report subjective performance assessments and perceived level of exertion (RPE)[73] in addition to general personal information (e.g. training frequency, performance in the past season, position on the team, demographic data etc.) and four genuine German sports performance motivation questionnaires (AMS: Achievement Motives Scale-sports; HOSP: Action orientation in sports; SOQ: Sport Orientation Questionnaire; VKS: Volitional components is sports).[74]

Experiment 2

The second experiment aims to unravel the central processes underlying enhanced athletic performance and how this information ties in with current models of fatigue. To research this underlying mechanism we initiate performance changes *via* a placebo ergogenic aid to isolate the central component of performance enhancement and then measure the underlying neurobiological processes using Electroencephalography (EEG).

Hypotheses Experiment 2

To our knowledge, no study has examined the central mechanisms underlying placebo induced performance enhancement by nutritional ergogenic aids. However, we assume that it is associated with changes in brain activity measurable by EEG. The data will therefore be analyzed in an exploratory fashion on the one hand and hypothesis driven on the other hand. We will attempt to replicate the findings of the metaanalysis by Crabbe and Dishman, suggesting that EEG responses during and after exercise show increases in alpha, delta, theta and beta activity.[64] We further aim to analyze the association between changes in EEG and changes in fatigue perception and the influence of peripheral physiology during exercise as suggested by Bailey and colleagues.[65]

Methods Experiment 2

As soon as Experiment 1 is evaluated, Experiment 2 will employ a similar study protocol as in Experiment 1, however, with a different group of athletes. Depending on the outcome of the first experiment, the mode of administration (food *vs.* capsule) that showed the largest performance enhancement will be used in the second experiment. A repeated measures design will be used with intervention (control *vs.* placebo) as independent variable and central and peripheral performance measures (objective and subjective) as dependent variables. In order to achieve a medium effect size of 0.25 (power=0.80, α=0.05) using a one factorial repeated measures analysis of variance (placebo *vs.* control), 30 athletes have to be included in the experiment. Athletes will be randomly assigned to one of 2 groups: Placebo (P) (N=15) or no treatment (control) (N=15). However, athletes in the placebo group will be told that they are given an ergogenic supplement that will enhance their endurance performance. EEG will be recorded from 64 electrodes according to the international 10-20 system before, during and after the 45 minute time trials at TT_b and TT_i.

Experiment 3

A third experiment will employ functional Near-Infrared Spectroscopy (fNIRS), which is a non-invasive measurement of the oxygen content of hemoglobin associated with neural activity. fNIRS is portable and even wireless instrumentation is available, enabling measurements in freely moving subjects. Based on the outcomes of the first two experiments, this third experiment is designed to enhance the understanding of the mechanism limiting and determining motor performance by integrating and regulating central and peripheral fatigue processes.

This experiment will further enable the specific investigation of the feed forward and feedback signaling pathways involved in performance and fatigue perception, because fNIRS can be used to measure both brain activity and muscle metabolism simultaneously.

The hypotheses for this study are based on the results of experiment 1 and 2, thus no exact information on the statistical analysis of this fNIRS experiment can be given at this time. However, the experimental procedure will be similar to that of experiment 2 and we expect to include further 30 athletes in this experiment.

CONCLUSION

This study protocol approaches a cross sectional area of research between exercise science, neuroscience and behavioural sciences. Most of the institutes interested in the combina-

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tion of these research areas, however, do not go beyond behavioural data due to a lack of neuroimaging equipment. Not only does this study clarify the issue of the influence of the mode of administration of an ergogenic aid on the degree of performance change. It will also show us, which brain mechanisms mediate this enhancement independent of the physiological effect any ergogenic aid may have. Data from the present study will thus enhance our understanding of the neurobiological basis of central factors limiting and enhancing physical performance and further our knowledge of the role of the placebo response and thus the psychosocial context on exercise performance. Furthermore, understanding the principle mechanisms underlying enhanced motor performance is relevant for the prevention and treatment of diseases which may be caused by a lack of physical activity (e.g. obesity, diabetes, heart disease, high blood pressure, etc.) or which may cause a decrease in the ability to be physically active (Morbus Parkinson, depression, etc.). Further this knowledge can be practically applied in the treatment and interaction with athletes in the context of sports medicine, physical therapy and nutritional interventions. Finally, investigating the placebo effect in the context of motor performance elicited by the administration of a nutritional ergogenic aid has implications not only for sports and the development of training strategies,[26,75] but also for the direction of future performance research and the controversial topic of (placebo) doping in sports,[76] raising not only ethical but also legal issues.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHORS CONTRIBUTIONS

EB: designed the study, conceptualized methods and research protocol, wrote the paper, will carry out the study, acquire and analyze the data. PE, KW: will support analysis of the data and paper writing. PE, AN: responsible for conception, study design and will support the preparation and funding of the study. PS: supported development of endurance protocol, conception of physiological measurements, will support data acquisition and study preparation. KW: advised on the study protocol, supported the writing process and revised the article. All authors reviewed and approved the final draft of the paper.

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VO_2 Kinetics during Different Forms of Cycling Exercise on Land and in Water

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ABSTRACT

Background: It is generally assumed that the physical properties of water improve aerobic metabolism by O_2 utilization of the working muscle particular if a great muscle mass is recruited. This study investigated the changes in VO_2 (VO_2-work rate relationship; ${}_{\Delta}VO_2/{}_{\Delta}WR$) during increasing work rates in different exercise conditions in water immersed exercise and on land based exercise.
Methods: In order to identify possible differences in VO_2 required for a given work rate twelve trained cyclists performed four incremental exercise tests. The tests comprised whole body work and leg work, both in water and on land and were conducted on the same, electromagnetically braked whole body ergometer.
Results: The ${}_{\Delta}VO_2/{}_{\Delta}WR$ curves were found to be similar in the four exercise conditions reaching from 11.9 to 12.4 ml·W^{-1} during water immersed exercise and 12.6 to 12.7 ml·W^{-1} during land based exercise respectively. When coupling arms with leg exercise the ${}_{\Delta}VO_2/{}_{\Delta}WR$ curves shift upwards at similar work rates indicating a higher oxygen demand for an enlarged muscle mass. The extra O_2 cost (${}_{\Delta}VO_2$) for recruited arms was lower in water immersed exercise compared to land based exercise (0.057±0.072 l ·min^{-1} and 0.367 1±0.057·min^{-1}, respectively; p=.000). Differences exist in the rate of performing physical work above ventilatory threshold two. Work load values attained on land based exercise surpass that of water immersed exercise (204.2 watts *vs*. 154.0 watts for whole body work and 227.1 watts *vs*. 150.0 watts for leg work, respectively).
Conclusions: Differences in ${}_{\Delta}VO_2$ at a given work rate are to be explained rather from a biomechanical point of view. More likely ${}_{\Delta}VO_2$ in water seems to be influenced by both familiarity of the task and fitness level. Exercise intensity in water need to be selected at lower levels than on land.

KEYWORDS: Whole body ergometry; VO_2 kinetics; Aquatic exercise.

ABBREVIATIONS: W: Water; L: Land; NIRS: Near-infrared spectroscopy.

INTRODUCTION

When coupling arms with leg exercise a higher oxygen demand at the same work rates is required compared with legs only.[1-5] In these experimental studies on Land (L) an enlarged muscle mass requires more oxygen, ranging from 0.04 til 0.36 l ·min^{-1} at equal submaximal stages. The workload-VO_2 relationship curve is shifted upwards at the same work rates indicating a higher oxygen demand for whole body work than work with leg only.

Based on several studies,[2,4,6,7] adding arm work to ongoing leg work leads to a higher VO_2max, ranging from 0.04 to 0.23 l ·min^{-1}. However, other researchers did not find significant deviations, measuring increases in VO_2max of 0.06 to 0.12 l ·min^{-1}.[3,8-11]

It appears that oxygen transport to the exercising muscles of the whole body is mark-

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edly elevated when referring to submaximum exercise stages. O_2 conductance depends on muscle mass and extraction capacity can be explained by vascular muscle bed.[12] In general oxygen consumption of vascular beds between the patterns of exercise is 0.2 l/min higher in whole body work.[13]

A slightly higher VO_2max is expected, if a large part of active skeletal muscles is involved at relatively high work rates close to the point of fatigue.[13] Adding arms to ongoing leg work increases mean arterial pressure through adrenergic vasoconstricting signals and is accompanied by a reduced cardiac output.[14] These restrictions in muscle blood flow limit the ability of the exercising muscle to extract the required O_2 and can be explained by the Fick relationship. The Fick equation states that VO_2 equals cardiac output times.

To date no scientific basis is provided for change in the dynamics of VO_2 for this setting in Water (W) immersed, in particular there are uncertainties with regard to the additional O_2-cost for whole body work. The physical properties of water change hemodynamic and metabolic responses: stroke volume increases by 30-50% and cardiac output at a given work load also increases about 25% through the Frank Starling mechanism.[15,16] From increased cardiac output as a result of increased cardiac filling pressure and lowered total peripheral resistance[17] it can be assumed that O_2 extraction in working muscles is more efficient in W than on L. However at present the effect is discussed controversial. Blood flow to oxidative muscles can also be affected if muscle pump generates a greater pressure gradient across the capillary bed and increases blood flow.[18] MacDonald, et al.[18] observed a slower response of both VO_2 and leg blood flow compared to the same work stages in supine position ergometry (which is similar to water immersed exercise) compared to an upright position during leg exercise at light to moderate intensity.

Hence in this study oxygen uptake and delivery to active muscle mass in different exercise conditions were determined. Rates of gas exchange reflect the relationship between O_2 delivery and O_2 uptake. They allow for an indirect assessment of the relationship of muscle blood flow and muscle oxygen uptake.[19] The present study tested the hypothesis, that coupling arm with leg exercise would increase metabolic load and the extra O_2-cost ($_\Delta VO_2$) in W would be similar to L; furthermore hemodynamic changes in W would improve O_2-extraction capacity. This is the case if the onset of anaerobiosis – determined by the gas exchange method (excess CO_2 above ventilatory threshold two; VT2) – for the particular workload occurs at a higher VO_2. The gas exchange measurements are relevant regarding energy generated from aerobic and anaerobic sources and energy metabolism. Aquatic exercise is a common and alternative method to land based exercise. Persons suffering from dysfunctions of the skeletal mucles and/or obesity will benefit from a change in the dynamics of VO_2 depending on a beneficial distribution of the blood flow in the muscles.

METHODS

Participants

Twelve trained male volunteers (age 35.1±5.4 years; body weight 79.4±11.4 kg; VO_2 peak 3.89±0.65 l $\cdot min^{-1}$) gave written and informed consent for participation. The study protocol was approved by the regional Ethics Committee (EKLU 11007).

Study Protocol

All subjects performed whole body work and leg work both in W and on L using the same whole body ergometer. This newly developed device allows for power output measurements as well as pedal arm forces (Reha-Aquabike, Swissrehamed, Chur, Switzerland, Figure 1). Prior to this study the new ergometer was validated for cardiopulmonary stress tests by determining its accuracy in W and on L. Before testing each subject underwent one practice session comprising both exercise patterns. The tests were conducted in a thermoneutral laboratory in W (water temperature 27-28 °C) and on L (air temperature 22-24 °C) at intervals ≥ 48 h and within 14 days. Work was varied by two minute adjustments in the workload (WHO-protocol: increment 25 watts, starting with 50 watts,[20] constant pedalling frequency at 70 revolutions per minute). The relative contribution of arm work to total work was set at 20% to strain the cardiovascular system close to maximum.[5] In order to avoid bias, a randomised cross over design study was conducted. All subjects were randomly allocated into two groups. Order of testing was assigned first in W – whole body and leg work – then on L. The other group started in reversed order.

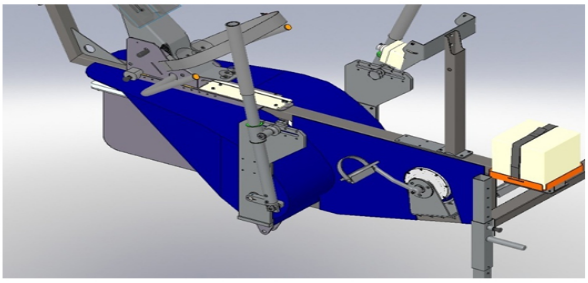

Figure 1: Photograph of the electromagnetically braked, whole body "rehaaquabike", measuring power output.

The backrest of the recumbent cycle ergometer was inclined at an angle of 110 °, the height adjustable seat ensured immersion to the xiphoid process. The participants were tested after a 3 h abstinence from food following a standardized meal and refrained from any physical exercise on the day before testing. All subjects abstained from taking any medication. Heart rate and electrocardiographic activity were continuously monitored using Medilog Darwin Holter System AR12 Plus; Schiller, Dietikon, Switzerland. Prior to the tests the gas analyzer for VO_2, VCO_2 and ventilatory parameters (K4b2, Cosmed, Rome, Italy) was calibrated due to Wasserman et al.[21] and pulmonary gas exchange and expired ventilation were measured breath by

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breath throughout the test. Values for oxygen consumption were referred to a given workload during the last 30 s and maximum capacity during the last 30 s with constant pedalling frequency.[22] To determine the onset of metabolic acidosis the CO_2-excess associated with hyperventilation was assessed (alveolar ventilatory threshold two; VT2) according to Wasserman et al.[21]

Statistical Analysis

To calculate the maximum sample size we examined the differences between whole body and leg work exercise in terms of VO_2max. Gutin et al.[3] gave examples, which differ by an effect size of about δ=91, α=0.05, power β=0.8 for a one-tailed test. Comparing it to the effect sizes which are common and using GPower 3.1. – Cohen describes an effect size of 0.8 as large – equating a sample size of twelve subjects.

Data are normally distributed and variances are equal (Shapiro-Wilk test). Differences in individual VO_2 at VT2 and peak power between trials ($p \leq 0.05$) were analysed using one-way analysis of variance (ANOVA) with Tukey`s post-hoc test (SPSS 17.0; SPSS Inc, Chicago, IL, USA) to discern differences between groups. Values are expressed as means±SE.

RESULTS

Twelve subjects were available for all of the four consecutive examinations. The contribution to the total power output from both arms showed no differences ($p>0.05$). In four tests VO_2 increased linearly ($r>0.90$; $p>0.090$) with increasing work rate up to the ventilatory threshold two (VT2) thus providing proof that the ergometer was accurately calibrated.

The increase in work rate related to the increase in VO_2 (${}_{\Delta}VO_2/{}_{\Delta}WR$) was similar ($p>0.05$) in the four exercise conditions and reached values from 11.9-12.4 ml•min·W^{-1} during water immersed exercise and 12.6-12.7 ml•min·W^{-1} during land based exercise (Table 1).

During whole body work a greater amount of oxygen in terms of VO_2 (ml·min^{-1}) was used at a given work load compared to leg work only. However, VO_2 responses were not significantly different ($p>0.05$). VO_2 curves were shifted upwards linearly for whole body work (Figure 2), both in W and for L each at similar power output levels during incremental work stages.

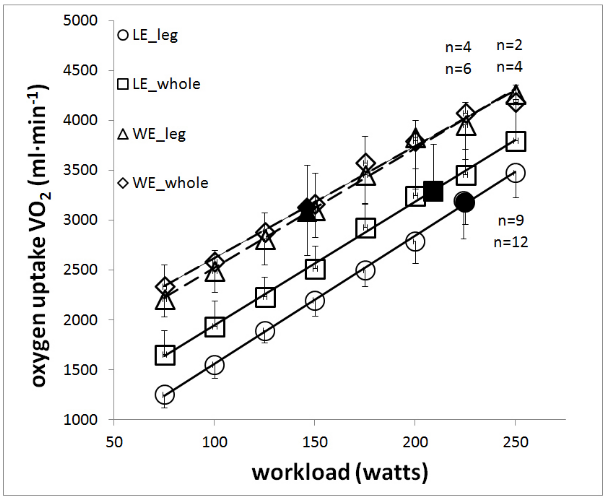

Figure 2: O_2-uptake at increasing work load in 4 replicated tests.

		L_leg	L_whole	W_leg	W_whole	p
${}_{\Delta}VO_2/{}_{\Delta}WR$	M	**12.7**	**12.6**	**12.4**	**11.9**	**≥0.582**
(ml·min^{-1}·watts^{-1})	SE	1.2	1.2	1.7	1.9	
VO_2_peak	M	3890.5	3884.6	3639.2	3728.7	**≥0.669**
(ml·min^{-1})	SE	649.8	613.2	601.0	485.5	
load_max	M	268.8^	254.7#	196.3	195.1	**=0.000/0.002**
(watts)	SE	36.1	38.6	37.8	34.7	
HR_peak	M	175.9	176.1	170.2	173.5	**≥0.665**
(b·min^{-1})	SE	12.3	12.6	13.1	12.4	
RER_peak	M	1.02*	1.03	1.12	1.09	
	SE	0.07	0.10	0.11	0.07	
VO_2_VT2	M	3199	3290	3086	3128	**≥0.704**
(ml·min^{-1})	SE	385	475	435	426	
load_VT2	M	227.1^	204.2*	150.0	154.0	**=0.000**
(watts)	SE	32.0	29.8	13.4	11.8	
VO_2_VT2/load	M	14.1^	16.1*	20.6	20.3	**=0.000**
(ml·watts^{-1})	SE	0.8	1.6	3.0	3.2	
HR_VT2	M	161.0	159.0	150.1	152.8	**≥0.096**
(b·min^{-1})	SE	11.3	12.1	11.3	10.7	
RER_VT2	M	0.94	0.97	1.01	1.00	
	SE	0.07	0.09	0.11	0.05	

Table 1: Values are means (SD). ^p=0.000 compared with W_leg; *p=0.000 compared with W_whole. #p=0.002 compared with W_ whole.

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Comparison of O_2-uptake at increasing work load (regression lines) in combined arm with whole (com) and leg ergometry (leg) in Water environment (W) and on Land environment (L). The VO_2 kinetic of all curves shows linearity over load stages but work in W displaces the curves upward from water resistance. Power output (workload in watts) displays external load on pedalling system but does not calculate demanded aerobic power from water resistance. VO_2-work rate relation from whole curves parallels that of leg and is displaced upward. The additional aerobic demand for recruited arms is represented at defined power output by the difference of the slopes from combined and leg-VO_2. Filled circles show the corresponding values at ventilatory threshold two.

The extra O_2 cost for recruited arms ($_{\Delta}VO_2$) was lower during water immersed exercise compared to land based exercise (0.057±0.072 l $\cdot min^{-1}$ and 0.367 l±0.057 $\cdot min^{-1}$, respectively; p=.000).

The magnitude of O_2 changes in W compared to L at work loads for the two work patterns influences the responses at the anaerobic threshold and at maximum effort: if exercise capacity is expressed as work load reduced work capacities at VT2 occur in W (leg work: 227.1 watts *vs.* 150.0 watts; whole body work: 204.2 watts *vs.* 154.0 watts) (Figure 2).

No statistically significant differences at VT2 were found when exercise patterns were matched for their VO_2 response. Moreover, no statistical significance could be reached for the relationship of O_2 requirements to maximum VO_2.

DISCUSSION

This study investigated oxygen uptake (VO_2) during four cycling exercises in W/L both for whole body and leg work.

During increasing work load the linearity of the VO_2-work relationships ($_{\Delta}VO_2/_{\Delta}WR$) were found to be nearly the same in the four exercise patterns.

VO_2 responses tend to result in higher values at a given work load during whole body work compared to leg work, both indicating additional oxygen consumption ($_{\Delta}VO_2$) in both W and L.

The observed shift of the VO_2 curves show that the extra cost for recruited arms ($_{\Delta}VO_2$) during land based exercise is more pronounced than that of water immersed exercise.

Differences at VT2 and related to maximum effort between land based exercise and water immersed exercise occur when exercise intensity is expressed in work load (watts). Leg work levels at VT2 attained 227.1 watts on L *vs.* 150.0 watts in W. Whole body work levels reached 204.2 watts on L *vs.* 154.0 watts in W.

However, VO_2 levels were unchanged when anaerobic threshold determined by the gas exchange method was related to their VO_2 responses.

The extent to which $_{\Delta}VO_2$ increases is not only attributed to usage of muscle mass. Research has confirmed that O_2-cost during arm work and whole body work is related to higher percentage of type-II-fibers in arm muscles[23,24] and that the amount of external work is greater.[19] Van Hall, et al.[25] and Jensen-Urstad, et al.[26] provided evidence that during whole body work more carbohydrates are utilized and more lactate is released than during leg. Moreover, extra oxygen is needed to overcome the forces of gravity. This is the case, when the pedaling axis during arm cranking is elevated above the horizontal position[27] or if the distance to arm crank axis is different.[28] Bergh, et al.[7] and Billat, et al.[11] linked a portion of the extra O_2-cost to posture and body position during whole body work.

The remarkable finding in the present study was that $_{\Delta}VO_2$ responses for recruited arms to a given workload is lower for W than for L. The following controversial issues are to consider:

- In W the oxygen demand of the working muscles is met more efficiently than on L due to improved hemodynamics in W.
- Biomechanical properties define the relation of VO_2 uptake and power output.

Studies reporting elevated oxygen uptake on L adress the main determinants: stroke volume and Mean Arterial Pressure (MAP). The latter is considered as a balance between local vasodilation and general sympathetic activity.[13] It is known that sympathetic activity to the vessels (vasoconstrictor signal) is opposed by baroreflex through increased blood volume and by vasoactive metabolites.[29] The feedback signal from the local tissue milieu regulates the demand of the muscles by adjusting blood pressure precisely.[30]

Studies which adress arm contribution give evidence that sympathetic nerve activity regulates blood pressure at the expense of flow.[13,14] When adding arm exercise to on-going leg exercise the Cardiac Output (CO) level can be restricted. MAP regulated by peripheral vasoconstriction can be a disadvantage with regard to muscle blood flow and oxygenation. If intense arm work is associated with a large MAP response arm vascular conductance and blood flow in working legs is reduced by 10%.[6] *Vice versa* when leg work is added to ongoing arm exercise vascular conductance and arm muscle oxygenation in the upper extremities decreases by 5%.[31] Such reductions in regional blood flow are mainly attributed to peripheral vasoconstriction to support the prevailing blood pressure.[13]

In W the local vasodilatation and general sympathetic activity seem to be proficiently balanced: from cardiac filling pressure through central blood shift ANP (Atrial Natriuretic Peptide) concentrations are elevated up to 2-3-fold.[32] The well-

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characterized ANP pathway regulates vascular tone – which is under sympathetic nervous system control – and renal sodium handling. ANP acts as a vasodilator via endothelial cells and promotes baroreflex-mediated activation. The pronounced sympatholytic effect of ANP leads to a reduced vasoconstriction in W compared to L.[17] The sympathicolysis corresponds well with lowered plasma noradrenalin concentrations.[33,34] Furthermore, larger ANP blood concentrations constrain the RAA-system by reducing the release of renine and aldosterone. The hormone-driven actions modify the fluid resistance within vessels thereby improving blood perfusion and O_2-extraction. Data derived from animal models also provided evidence of improved blood perfusion in regional vessels of the musculature.[35,36]

In this paper the hypothesis was tested that, depending on O_2 flow in the working muscle, O_2 supply will meet the O_2 demand of the working muscle more efficiently. The metabolic acidosis in a graded exercise test would occur later reflecting a proficient availability of O_2 for the muscles. Therefore VO_2 rate at VT2 and maximum effort were monitored. In fact VO_2 levels showed equal proportions of aerobic and anaerobic potential in all cycling exercises. Thus the hypothesis is to reject that the metabolic conditions of cycling exercises in water are advantageous. It can therefore be assumed that O_2 extractions are similar both on L and in W. Probably the contribution of the processor reflex provides different but adequate mechanisms for the interdependent regulation of the cardiac output and the perfusion of the working muscle.

Differences in $_{\Delta}VO_2$ can be rather explained from a biomechanical point of view, the transfer of metabolic energy into physical work. The total power output depends on the surface resistivity of air or water. Due to buoyancy arm power is better preserved than that of the leg because of the contractile properties and the content of myosin of the arm muscles.[37] Last but not least the extra O_2-cost can be explained by the isometric exercise component required for the stabilization of the exercising body.

The $_{\Delta}VO_2$ values can be explained with the much higher relative percentage of VO_2max in W reached by well-trained. At higher work load the $_{\Delta}VO_2$ are a result of the participant`s familiarisation with whole body exercise.[38] Recommendations regarding performance improvements normally include information on appropriate training load. If the maximum workload reached on L is transferred to exercise in W, it is to consider that the resistance that water provides acts on moving limbs and require adaptations for safe working especially for those with medical conditions. Based on the present study aquatic exercise shall be performed with reduced mechanical workloads if the oxygen uptake in water immersed exercise is to be the same as on land based exercise.

For years, the scientific community has been responding to the lively question of oxygen delivery to superimposing arm exercise with leg exercise.[39] We addressed the metabolic responses of added arm work to ongoing leg work in W in particular. We only measured respiratory responses but did not assess the distribution of the regional blood flow in arms and legs. The use of Near-infrared spectroscopy (NIRS) would give insight into blood flow redistribution.

CONCLUSION

This study illustrates the importance of the selection of the correct exercise intensity in W. The application of exercise intensities assessed on L leads to an overload in W. Our results suggest a reduced workload in W of 50.2 watts for whole body work and by 77.1 watts for leg work. This estimate applies to 70 revolutions per minute in water cycling.

Predicting VO_2 based on work load can lead to an overestimation of energy expenditure, if threshold patterns are not taken into account. Thus, the oxygen requirements of whole body work in W at a high intensity steady state will not exceed those of leg only. Furthermore the influence of W on VO_2 supply to the exercising muscles is only marginal. The cardiovascular system seems to regulate its O_2-supply via modulations of vascular conductance by MAP and a differential contribution of cardiac output similar to exercise on L.

CONFLICTS OF INTEREST

The authors declare that the main outcome obtained for the regulation of the intensity in water is not influenced by competing interests.

AUTHOR'S CONTRIBUTIONS

BV, JG designed the study, MF and JG participated in the data collection. MF, KK and CS drafted the manuscript. CS, BV and JG gave critical comments on the manuscript. All authors checked and approved the final version before submission.

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