Is functional movement screening indicative of lumbopelvic and trunk kinematics during a prolonged non-exhaustive running bout?

Alessandra Vairo Peres Boratino

University of Jyväskylä
Faculty of Sport and Health Sciences
Master Thesis in Biomechanics
October 2022

Primary Supervisor: Dr Timo Rantalainen (University of Jyväskylä)

Co-Supervisor: Prof Dr. Janne Avela (University of Jyväskylä)

Advisor: Dr. Victor Hugo de Oliveira e Souza (Aalto University)

Abstract

Boratino V.P.A. 2022. Is functional movement screening indicative lumbo-pelvic and trunk kinematics during a prolonged non-exhaustive running bout?. Faculty of Sport and Health Sciences, University of Jyväskylä, Master's Thesis in Biomechanics, 46 pages, 1 appendix.

Functional screening tests are performed in sports settings aiming to recognize neuromuscular deficits and asymmetries, guiding preventative strategies often expecting to improve the running mechanic. So far, no studies have validated those tests in a prolonged run. The findings may provide clinicians with insights into the utility of conventional physical assessment. The purpose of the study was to investigate the association of 3D trunk and lumbopelvic kinematics during a non-fatiguing running and four functional screening tests.

Methods: Ten recreational runners were included (age 27,91±5 y). The protocol was 3 repetitions of each functional test (squat, single leg squat, lunge and hurdle step) followed by a 40-minute over-ground running at a self-selected pace. Hip, pelvic and trunk kinematics were assessed with a 3-D motion analysis

Results: Similar trunk, lumbopelvic and hip kinematics pattern during the knee peak flexion during the midstance; few subjects have had interlimb kinematics asymmetries during running (pelvic list, pelvic rotation and lateral bending- $p<.001$). Running and functional tests demonstrated major differences ($p<.001$) in lateral bending and pelvic list, pelvic tilt, axial and pelvic rotation. In addition, there were positive, moderate to strong correlations only for pelvic list and rotation among running and functional tests.

Discussion/conclusion: There were no signs of fatigue, a similar kinematics were observed in running and tests. The interlimb asymmetries could be caused by lack of neuromuscular control or anatomical differences. The correlation between lumbopelvic and trunk were inconsistent, so these tests should not be used as the only source of neuromuscular motor.

Keywords: running, functional tests, kinematics, 3D motion analysis.

Summary

Abbreviations

FMS: Functional Movement Screening

RRI: Running-related injuries

EMG: Electromyography

IMU: Inertial measurement unit

3-D: Three-dimensional

Ll: Lower limb (hip, knee and ankle)

CKC: Closed kinetic chain

SLS: Single-leg squat

RL: Right leg

LL: Left leg

H1, H2, and H3: Hypotheses

S0: Subject + number of identifications

1. Introduction

Physical activity (PA) is one of the most powerful sources to keep our body and mind healthy, thereby decreasing disability and all-cause mortality (Fields et al., 2010; Ooms et al., 2013; Samitz et al., 2011). Fortunately, the interest in PA in recent decades has increased not only from a scientific point of view but also from participants and politics (Stamatakis et al., 2008). Running has been acknowledged as one of the most popular PA for those who are seeking a healthier lifestyle due to its accessibility, health, and social benefits (Clermont et al., 2019; de Oliveira et al., 2017a; Ooms et al., 2013; Stamatakis et al., 2008; van der Worp et al., 2015). The number of runners is increasing worldwide (Fields et al., 2010; Stamatakis etal., 2008). To illustrate, in Australia running and jogging accounted for 4%, 7%, and 7,4% of all sports participation and PA through 2005-06, 2010, and 2013-14, respectively(*Australian bureau of statistics.* 2010).

Currently, the sports industry has been working as a health promoter (Ooms et al., 2013), attracting runners' attention from novice to competitive level, which promote runners' self-motivation to achieve better performance. The popularization of running has countless benefits; however, many runners have progressed their training without a previous running experience and physical assessment, which may predispose them to running-related injury (RRI) or affect performance. (Hespanhol et al., 2016)

RRI are common and accounted for 19,4% to 79,3% in recreational runners (Fields et al., 2010; Lun etal., 2004; van Gent et al., 2007). The predominant anatomical location of such injuries is the lower limb (Franke, Backx, & Huisstede, 2019; Hespanhol Junior et al., 2016; van Gent et al., 2007), frequently related to intrinsic and extrinsic factors, such as biomechanical alterations, muscle imbalances and training errors (such as fast progression in training volume, speed or mileage) (Aderem et al., 2015; Clermont et al., 2019; Dierks et al., 2010; Fields et al., 2010; Buist et al., 2008; Nielsen et al., 2012). Due to the health and economic impact, effective preventive strategies are crucial (Fields et al., 2010; Hespanhol et al., 2016; van der Worp et al., 2015). Thus, clinicians and researchers have proposed clinical biomechanical tests and complex running analysis as preventative tools and performance optimization (Ugalde et al., 2015; Whatman et al., 2011). Thus, different functional movement patterns, such as the functional movement screening (FMS™), and single-leg squat, are being used in clinical settings to recognize possible muscle imbalances, limb asymmetries, and lack of flexibility (Whatman et al., 2011). In addition, analysis of running biomechanics on a treadmill has also been used to inspect any significant biomechanical imbalances (Whatman et al., 2011).

However, there is a lack of validation over those functional tests and running kinematics. To date no studies have been found correlating those tests with a long over-ground non-fatiguing running. Most of the running protocols were performed on a treadmill with a non-realistic time-speed parameter. Specificity must be considered, as the real running environment (treadmill vs. over-ground) and the total running time. Therefore, due to the lack of validation and studies on self-selected pace and over-ground running, the purpose of this study was to assess and validate specific functional movement screening tests, with over-ground running biomechanics in a self-selected speed for 40 minutes in recreational runners.

2. Running

Running is one of the most popular exercise modalities in the world. The number of recreational runners have been increasing due to its accessibility, health and social benefits. (Clermont et al., 2019; de Oliveira et al., 2017b) Consequently, a running literature explosion and immense progress in technical devices (biomechanical) deepen our understanding of running (Novacheck, 1998).

The relationship between running biomechanics, performance and injuries has become more apparent in recent decades, even though there is still a long way to comprehend the link between some biomechanical and musculoskeletal imbalances with injury. However, there is no evidence supporting that only an 'imperfect' mechanics will lead to an injury unless there is a previous one or excessive training progression, thus RRI are multifactorial. (Bramah et al., 2018; Ceyssens et al., 2019; Nielsen et al., 2012; Saragiotto et al., 2014)

The purpose of this thesis was to explore the associations between functional tests and running kinematics; consequently, it is essential to understand basic concepts and why the investigation of biomechanical risk factors with those tests are clinically relevant. Therefore, this chapter aims to pinpoint the most known and relevant aspects of running biomechanics and biomechanical aspects of RRI.

2.1. Running biomechanics

As a result of the advance in biomechanical research and devices, muscle activation, running kinematics, and kinetics have become more accurate, which allow us to determine each phase of the running cycle quantitively. This section will introduce the typical conceptualisation of running used in biomechanical analyses.

The running cycle can be divided into three stages: stance, swing, and flight (Nicola & Jewison, 2012; Novacheck, 1998). The stance is characterized by the foot strike, midstance and toe-off, followed by the swing phase and the flight phase in which both feet are off the floor (Nicola et al., 2012). Compared to the gait cycle, the running toe-off phase occurs before 50% of the gait, meaning that the swing phase is greater than 50% of the cycle, directly related to speed (Figure 1). Another fact that differentiates running from walking is the float or flight phase (between stance and swing), where the lower body is not in contact with the floor (Dugan et al., 2005; Novacheck, 1998; Segers et al., 2006; Nicola et al., 2012). The running cycle can also be divided into absorption and generation phase, and on the contrary, these phases are not affected by speed (Figure 1); the center of mass is altered during the absorption and generation phase, the velocity decreases horizontally, and it is propelled upward and forward, respectively. (Novacheck et al., 1998)

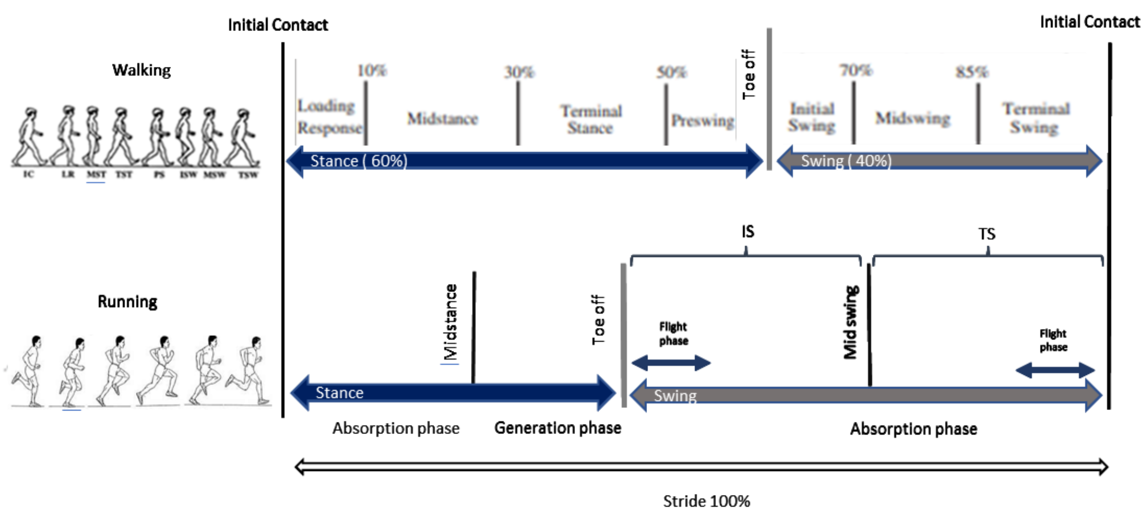


Figure 1. Walking and running phases. IS, initial swing, TS, terminal swing. Figure modified from Novacheck (1998) and Dugan & Bhat (2005).

Running involves complete coordination of the body. The synchronized action of joints, muscles, and tendons work like an orchestra, where each segment or muscle has a crucial role. Still, without the action or "cooperation" of others, the movement can either be altered or not performed. This "orchestra" relies on the interrelationship of factors as neuromuscular control, adequate range of motion, joint congruity, muscle condition, and previous experience, to name a few.

The stance phase can be divided into absorption or eccentric phase and propulsion or concentric phase, each marked by specific joint couplings. Due to the continuous and repetitive running cycle, the stance phase is characterized by absorption of impact forces, and in normal circumstances, it is firstly absorbed by the foot and the ankle and then transferred up to the kinetic chain. (DeLeo et al., 2004)

In order to attenuate the shock, the foot is supinated during the first strike, before the midstance it pronates allowing the foot to adapt to the surface, and lastly, during the toe-off, the foot supinates again, allowing the first metatarsal ray to act as a rigid lever for the runner's propulsion. Concurrent with the pronation, the talus adducts and medially rotates, the tibia internally rotates, and the knee internally rotate, adduct and flexes (peak knee flexion). The hip is slightly flexed (± 30º) from initial contact to 30% to 40% of the stance phase. At the beginning of the stance, the hip adducts and slightly internally rotates. Due to the contralateral swing leg, the pelvis rotates anteriorly and externally to the femur, decreasing hip internal rotation and assisting more supination. Thus, hip transverse plane motion is mainly external rotation, which begins around 20% of stance. (DeLeo et al., 2004; Dugan et al., 2005; Nicola et al., 2012)

The preparation for the toe-off or propulsive phase is represented by the supination of the foot, and so change in all kinetic chain, the tibia externally rotates (knee joint) while extending. Moreover, supination allows the foot to become rigid for the push-off phase, where the body is propelled forward. For the remaining phase, the hip externally rotates, abducts and extends, once the foot leaves the floor, the hip achieves its maximum extension, and later maximum knee flexion angle. The most notable kinematics changes occur within the sagittal plane. (Dugan et al., 2005; Nicola et al., 2012)

The knee is a predominant hinge joint, however, due to the difference between femoral condylar geometries studies have proven that the knee has six degrees of freedom (Gray et al., 2019; Kozanek et al., 2009; Postolka et al., 2020). Knee rotations are referred to as the tibiofemoral motion, and it is essential for a healthy and functional knee joint; however optical motion capture has limitations due to soft tissue artefact, hence an accurate alternative method is to pin-screwed directly to the bones, or single or dual-plane fluoroscopic analyses (Gray et al., 2019; Postolka et al., 2020). The last two methods are invasive or time-consuming, hence most of the studies assume rotations and translations in the knee joint based on 3D analysis, the present study refer to those studies, so caution must be taken when interpreting this data.

Studies have found that the trunk flexes during the stance phase, peaking around mid-stance, and laterally flexes concomitant with pelvic drop (Schache et al., 1999) (Figure 2). However, Preece and colleagues have found that trunk flexion and anterior pelvic tilt, lateral bending and pelvic drop presented an opposite movement during the stance phase. There is a contralateral pelvic drop at the initial contact then an ipsilateral drop (elevation towards the stance leg) toward the toe-off phase. Moreover, during early initial contact the trunk tends to laterally bend toward the stance leg, and as the pelvis elevates towards the stance leg, the trunk then changed to a neutral alignment (Preece et al., 2016). The pelvis is externally rotated from foot strike to mid-stance, then turns to a neutral position for a toe-off phase, and during the swing it internally rotates(Novacheck, 1998).

Studies have been suggesting that lesser pelvic and trunk movement are directly related to energy economy, and it might decrease the risk of RRI(Preece et al., 2016). Studies are performed within different conditions, thus we need to carefully interpret/compare the data, considering variables that affect the kinematics, such as the experience (novice to elite), speed and duration of the protocol(fatigue).(Koblbauer et al., 2014)

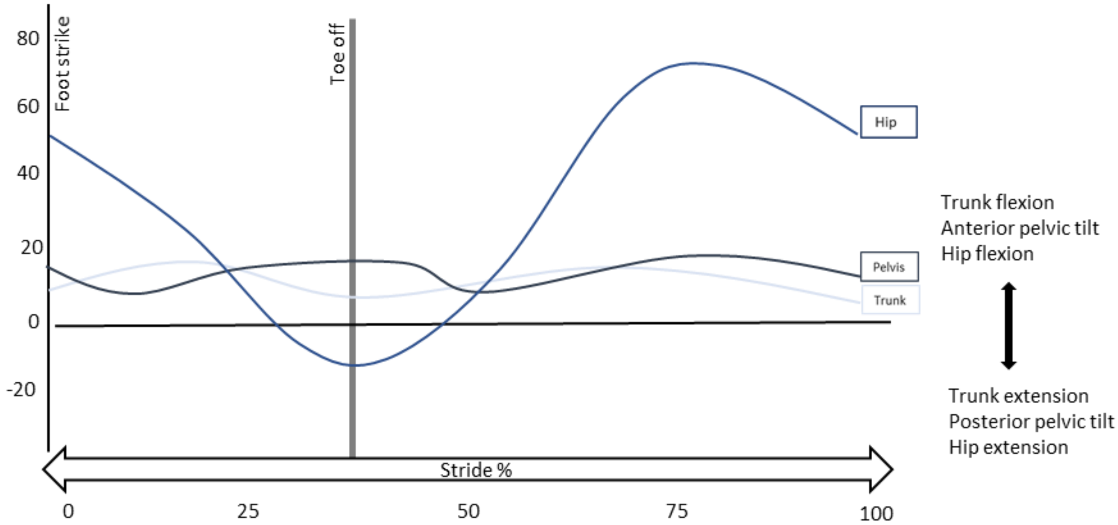


Figure 2.Sagital plane rotation of the hip, pelvis, and trunk. Modified from Schache, 1999, based on Thorstensson et al.1984]; Ounpuu 1990; Novacheck 1998.

During non-exhausting running for healthy runners, most of the joint coupling and timing is synchronous, with joint peaks occurring around midstance; however, asynchronous joint timing among subjects does exist and might lead to injury. Differences in joint coupling times among subjects might vary based on running experience and biomechanical differences. Thus, an individualized assessment is needed in clinical settings to understand an individual's specific biomechanical coupling pattern. (DeLeo et al., 2004; Dierks et al., 2010; Ferber, 2014)

The joints coupling of the lower limb are well documented and understood; however, we still lack literature about the lumbo-pelvic-hip complex(Schache et al., 1999).

2.2. Running related injuries

Despite the health benefits, researchers have shown that RRI in the lower limb is high among runners. RRI is multifactorial, in which training characteristics, less running experience, and previous injuries are among the most significant factors contributing to an injury (Buist et al., 2010; Linton et al., 2018; Nielsen et al., 2012). When the mechanical load is higher than the soft-tissue capacity or adaptation, an injury can occur (Dye et al., 2005).

A recent review that analyzed studies with different runner levels concluded that experienced runners presented the lowest risk for injury; on the other hand, novice runners demonstrated a greater incidence of injury compared to recreational runners' incidence per 1000 h of running, 17.8 (95 % CI16.7–19.1) and 7.7 (95 % CI 6.9–8.7) respectively (Nielsen et al., 2013; Videbæk et al., 2015). Moreover, a retrospective cross-sectional study conducted in the United Kingdom with 1145 respondents has shown that runners with 6 months or less of running experience were 1.53 times more likely to be injured compared to those with 2-5 years of running experience, 1.98 times more likely to be injured compared to those with 5-10 years of running experience, and 1.73 times more likely to be injured than those with over 10 years running experience. (Linton et al., 2018). Experienced runners present lower chance of RRI, which might be explained by musculoskeletal adaption to the load (Linton et al., 2018) and self-manage about their body and symptoms, being able to adjust the training.
Besides, non-modifiable factors may increase the risk of RRI, such as sex, anatomy, and age. Evidence has suggested that risk profile differs between sex; men are likely to get injured by modifiable factors as training loads, and females are more likely to get injured due to anatomical characteristics and musculoskeletal imbalances. (Buist et al., 2010)
Modifiable and non-modifiable factors may contribute to altered running mechanics, recognized as a factor for developing injuries (Dierks et al., 2010).
In addition, studies with kinematic and kinetic analyses have shown an increased hip internal rotation and adduction, knee internal rotation, and hip and trunk muscles imbalances cause women to be more vulnerable to musculoskeletal injuries during running practice than men (Clermont et al., 2019; Schmitz et al., 2014). Even though each runner´s biomechanics and neuromuscular control are unique, there exists many similarities and a most accepted movement (e.g., typical) pattern (Nicola et al., 2012). Due to the above evidence identifying the mechanical underpinning of RRI an individualized functional physical assessment and preventative strategy to reduce and treat RRI should include consideration of the runner´s biomechanics.

3. Functional screening tests

Pre-season screening in athletes is paramount; research teams and clubs have been investing an expressive amount of time testing athletes in order to obtain a precise result, either aiming to improve technique, decrease the risk of injury or manage the risk profile. The importance of screening has turned into another perspective, either to competitive athletes or recreational sportspeople. Formerly, those screenings focused mainly on individual muscle function or joint; however, those parameters do not represent the actual sport skill. Currently, it also considers functional movement patterns, which assesses multi-joint segments and muscle chains; in addition, it might replicate the kinematics of specific sports activity (Mottram et al., 2007). It is well accepted that the body has "regional interdependence," in which there is a direct relationship between different body segments; thus, any imbalance in one distal segment might affect the proximal one or vice-versa. (Cook et al., 2006a; Cook et al., 2014a)

Considering the impact of performance and injuries on the athletic population, many clinical biomechanical tests to predict musculoskeletal imbalances and altered performance have been proposed in the literature. Physiotherapists and sports physicians have been using those tests to identify modifiable intrinsic risk factors which may lead to poor performance or injury(Moran et al., 2017a). Functional movement for the lower extremity is mainly weight-bearing and can be visually assessed and aim to recognize neuromuscular deficits, asymmetries and range of movement (Ressman et al., 2019). Abnormalities in the frontal knee plane can be easily recognized. Thus those tests are a time- and cost-effective screening tool compared to more sophisticated biomechanical analysis, such as 2D and the gold standard 3D(Stensrud et al., 2011).

Some studies have suggested a link between lower limb kinematics during functional tests and running (Whatman et al., 2011; Willson et al., 2008); however, most of the running or jogging protocols were performed on a treadmill with pre-selected speed, which may not reflect the actual subject movement pattern during the real practice. Clinicians plan their treatments based on those results; however, the evidence is still weak. More studies are needed to clarify the correlation between those functional tests and actual movement (e.g., running) (Whatman et al., 2011). Information about the used functional tests is presented below.

3.1 Single leg squat

The single-leg squat (SLS) is a simple test in which the subject performs a squat in a single-leg stance. It is mainly used to assess the quality of movement and control of the lower limb and core. The movement pattern relates to landing, running and cutting tasks; thus, this test is commonly used in sports settings. (Ressman et al., 2019; Ugalde et al., 2015)

The assessment criteria vary among studies, some authors suggest a multisegmented approach while other more superficial assessments for knee and ankle. Regardless of the criteria, important observations can be drawn from it, as lack of motor control, Ll movement quality and dynamic alignment (e.g., pelvic drop, internal femoral rotation, knee valgus and foot pronation) to name a few. (Rees et al., 2019; Ressman et al., 2019; Willson et al., 2008; Willy et al., 2011)

Most of these patterns might also be present in running and jumping maneuvers. Therefore, there is a vast literature on SLS in subjects with and without Ll injuries. According to Whatman et al., 2011, the SLS and its variations are not time-consuming, and it can highlight the subject's kinematics during running and walking, thus a useful screening test.

3.2 Functional Movement Screening test (FMS™)

The FMS™ test was first published in 2006 and updated in 2014 by Cook and colleagues. (Cook et al., 2006a; Cook et al., 2006b; Cook et al., 2014a; Cook et al., 2014b). FMS™ test is an integrated approach assessing multiple domains of function (Cook et al., 2006a; Cook et al., 2006b; Cook et al., 2014a; Cook et al., 2014b; Minick et al., 2010).

The FMS™ visually assesses the individual's movement pattern and specific neuromuscular deficits and asymmetries; it is composed of seven movements that are scored based on the execution, asymmetries and compensatory movements(Hotta et al., 2015; Minick et al., 2010.; Moore et al., 2019; Moran et al., 2016, 2017b). The test is based on the analyses of deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and rotary stability tests. In which each test can be scored from 0 -3, composing a score out of 21. These fundamental movement patterns are designed to provide detectable deficits in the performance of basic locomotor, manipulative, and stabilizing movements. (Cook et al., 2014a)

Daily life or sports activities require a well-development fundamental movement pattern (Minick et al., 2010). Even high-level athletes who perform complex motor actions present compensatory movements during extreme functional positions. It might be related not exclusively to weaknesses and imbalances but also the lack of stability and mobility (Cook et al., 2014a). Thus, lack of mobility, strength, balance and coordination, and neuromuscular deficits observed in functional movements might reflect some deficiencies in sports practice, leading to poor performance or increasing the chance of sustaining an injury. Due to the body's region interdependence, any restriction or deficit in one segment might lead to a specific mechanical overload or inefficient performance. (Frost et al., 2012; Minick et al., 2010)

3.2.1 Description of the Functional Movement Screen™

The official FMS™ test consists of seven functional movement patterns; due to the scope of this study, only three tests were performed: deep squat, hurdle- step, inline lunge. Those focus on Ll, lumbopelvic and trunk alignment. The description of the tests correspond to the official FMS™ guidelines (Cook et al., 2014a; Cook et al., 2014b).

- Inline lunge
    - Purpose: This test aims to simulate stresses during rotational, decelerating, and lateral type movements. The subject stands in a narrow base of support, where the Ll is in a scissor-style position. This position requires a torso and Ll proper alignment to resist rotation motion.

Moreover, the test assesses Ll mobility and stability and quadriceps flexibility

- Description: The subject stands in line. The movement consists of lowering the back knee towards the floor (touching it), maintaining a vertical posture and then returning to the starting position. The test is performed up to three times bilaterally in a controlled and slow manner. (Figure 3A).

- Deep Squat
    - Purpose: Deep squat is an important movement in most of the powerful actions of the Ll. This simple test can assess the symmetry and the functional mobility of the Ll
    - Description: The subject assumes the starting position by placing the feet aligned in the sagittal plane and shoulder-distance apart. The individual is instructed to perform a deep squat while maintaining the torso upright, heels and stick in position. (Figure 3B).

- Hurdle- step
    - Purpose: This test challenges the body's proper stride mechanics during a stepping motion. It requires appropriate hip and trunk stability and coordination during the stepping motion, also an adequate unipedal stance balance. The hurdle step assesses bilateral functional mobility and stability of the Ll.
    - Description: The individual assumes an upright posture with feet hip distance apart touching the base of the hurdle. The hurdle is then adjusted to the height of the subject's tibial tuberosity. The subject is asked to step over the hurdle, lift the foot toward the shin, and maintain the Ll alignment, and touch the heel to the floor (without accepting weight) while supporting the stance leg in a straight position. The moving leg is then returned to the starting position. (Figure 3C).

Figure 3. Functional Movement Screening. A: Inline lunge. B Squat. C: Hurdle-step. Extracted from original FMS™ document.

3.3 Injury Prediction

The majority of studies have used the FMS as a tool to predict injuries in team sports, military and firefighters personnel(Bushman et al., 2016; Chimera & Warren, 2016; Frohm et al., 2012; Kiesel et al., 2007; Mokha et al., 2016; Moore et al., 2019; Schneiders et al., 2011), just a few with runners (Agresta et al., 2014; Hotta et al., 2015; Loudon et al., 2014.; Olveira et al., 2017). Even though FMS has received widespread recognition based on injury prevention, there is conflicting evidence.

It is important to notice, that FMS is a screening protocol, consisting of 7 movements (score up to 21) related or not to the sports action. A recent meta-analysis(Moore et al., 2019) has found a small effect size and highlights the heterogeneous methodologies among studies contributing to inconsistent results. In addition, it is suggested that the score threshold of ≤ 14, would indicate high injury risk profile, but it does not seem accurate, one reason is that it ignores the sports specificity. In contrast another review has found that athletes with ≤ 14 have a greater chance of sustaining a musculoskeletal injury(Bonazza et al., 2017).

Notwithstanding, very few studies have focused on the presence of interlimb asymmetries during the FMS, however studies with senior athletes shows that this population had a more pronounced asymmetry than in young athletes, and it was a stronger predictor of injury, which might be an indicative of motor control deficits. (Moore et al., 2019)

Therefore, the movement screening should be part of a wider musculoskeletal examination, and the tester should carefully select the tests that are appropriate for the sport (Frost et al., 2012; Moore et al., 2019b). Previous studies have suggested that the hurdle step, in-line jump and SLS require similar motor patterns as running, and the squat requires global strength and LL mobility which are essential characteristics for prolonged running(Crossley et al., 2011; Loudon et al., 2014; Ressman et al., 2019; Whatman et al., 2011). Suggesting that these tests could be included in running screening battery aiming to detect musculoskeletal unbalances and motor control deficits. In addition, the preventive assessment should also include a specific sports biomechanical analysis(Gamble, 2013).

4 Purpose

Considering the popularity of running as a hobby, the high prevalence of RRI and its negative impact for recreational runners; the understanding of possible risk factors and possible correlation between lumbo-pelvic control for functional movement and running would potentially help clinicians and coach to delivery a better physical preparation. Therefore, main objective of this thesis was to assess the association of lumbo-pelvic and trunk kinematics during running and four functional tests in recreational runners.

The main research questions and hypotheses were:

1. Can recreational runners sustain the kinematic pattern during a self-selected 40-minutes run? Will they present interlimb asymmetries, and will it increase throughout the protocol?

   H1.1: Runners will present a similar movement pattern throughout the running protocol

   H1.2: Runner will present interlimb asymmetries, which will not increase during the protocol
2. Will recreational runners present a similar interlimb kinematic pattern during the functional tests?

   H2.1: Runners will present a slight interlimb asymmetries during functional tests that require higher level of motor control, such as SLS and step hurdle.

   H2.2: Runner will present similar interlimb kinematics during tests with bigger stance.
3. Will there be a correlation of lumbo-pelvic and trunk kinematics between running and functional tests?

   H3.1: Runners will present a positive and moderate correlation between running, step, SLS and lunge.

   H3.2: Runners will present a poor and negative correlation between running and squat.

These questions and hypotheses were based on previous studies suggesting that exhausting-running protocols alter the kinematics and the neuromuscular control(Apte et al., 2021), that subtle interlimb asymmetries are expected due to anatomical differences(Carpes et al., 2010; Radzak et al., 2017; Schache et al., 2002). Lastly, previous studies have shown that single-leg stance movements are highly correlated to running (Schreiber & Becker, 2020; Whatman et al., 2011).

5 Methods

5.1 Participants

Twelve recreational runners (6 female and 6 male) were recruited via Facebook groups and university email based on the inclusion criteria: age 18 to 40 years old, healthy and no injury in the last 3-month, body mass index 18- 30, and running experience of at least three months and weekly training of 12k-50km. Participants were informed about the protocol and signed a written consent. The study was granted ethical statement by the University of Jyväskylä Human Sciences Ethics Committee (Diary number 606/13.00.04.00/2020).

Demographic and running data can be seen below (Table1 and Figure 4).

Table 1.Demographic data

	Height	*Weight*	*Age*
Mean	1,71	64,22	27.91
Std. Deviation	0,0789	9,20	5.04
Minimum	1,61	55	22
Maximum	1,84	85,5	38

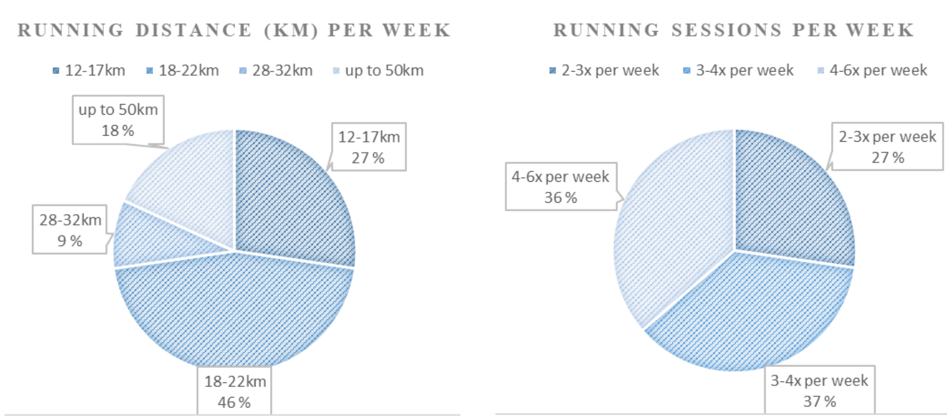


Figure 4. Running data: distance and sessions per week.

5.2 Instrumentation and experimental set-up

The protocol was conducted at the track and field area in the Hipposhalli sports complex in Jyväskylä- Finland, and it is described in figure 5. The capture area was equipped and operated with reflective marker- based 3D motion capturing system (Vicon Motion System, Oxford, UK) with 12 cameras with sampling frequency of 200 frames/second, five force plates, EMG and timing gates (Figure 5A). The protocol was part of a bigger project and force plate, timing gates, and EMG data were not used in the present study. Only kinematic data capture for functional tests and running were analyzed.

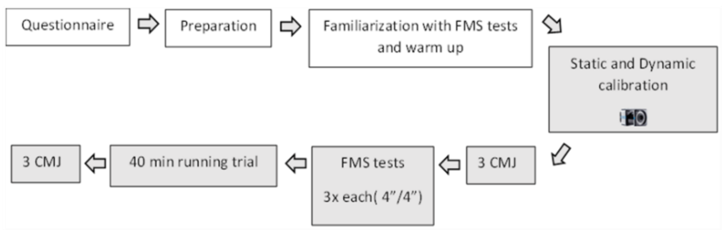
The capture volume was identified as the capture area and calibrated according to the manufacturer instructions using the Vicon T calibration wand prior to each trial. The precision of the calibration reported by the software accepted was less than 2 mm at worst and the calibration was repeated until an acceptable calibration was achieved. Timing gates were positioned at the beginning and end of the capture area (10 meters).

Participants filled out a questionnaire about their running experience, training, and sports background. All participants ran in their personal shoes, wore shorts and a sleeveless t-shirt. Reflective markers were placed bilaterally on specific anatomical landmarks, including acromion process, seventh cervical spinous process, manubrium sterni, anterior and posterior superior iliac spine, lateral and medial femoral condyles, lateral shank, medial and lateral malleolus, heel, first and fifth metatarsal heads, totalizing 24 markers; and the 2 clusters made with thermoplastic base plate with 4 reflective markers, forming a rectangular shape were placed on the lateral and distal aspect of the thighs. In order to guarantee the marker's position, double tape, tape and elastic bandage (Coban) were used (Figure 5B), and to avoid inter-tester variability two operators were placing the markers for each subject.

Prior to the data collection, the sequence of the functional tests was randomly selected; runners had the chance to perform the tests and ran one lap on the running track (200m) to get familiar with the protocol, and to unsure the devices were working properly. Participants stood up with feet hip-width apart in the capture volume for the static and dynamic calibration.

The starting position for the 3D capture for the functional tests, was always at the same point and standing pose, except for the lunge test, in which subjects stayed upright with feet in line. Participants performed three repetitions of each test, respecting counts of 4 seconds for each phase of the movement, 15 seconds between each repetition, and 1 minute between trials. After that, three counter-movement jumps were performed. A unique tester was guiding the subjects and timing the tests.

Following these tests, the medial femoral condyles and malleolus markers were removed. The subject stood up in the capture volume while EMG, force plates, timing gates signals, and motion capture were checked. Runners were instructed to run at a self-selected pace on the 200m track for 40 minutes. Lastly, participants performed 3 CMJ (Figure 5).



A

B

Figure 5. Experimental design. A: Capture volume. B: Subject preparation with EMG and reflective markers.

5.3 Data analysis

Vicon software was used to compute the 3D trajectories of the reflective markers within the capture volume. The markers were identified manually, and gaps were filled within the Vicon workstation software after which the trajectories were exported and subsequently imported into the open-source musculoskeletal modeling software OpenSim (Delp et al., 2007). The data was transformed from Vicon to OpenSim joint coordinate system following the right-hand rule, where *x*- direction forward, *y*- direction up, *z*- direction right.

The kinematics variables of interest were lateral bending and rotation of the trunk; pelvic rotation, drop and tilt; hip abduction-adduction and rotations, given the difference between sides, left and right leg were analyzed separately (LL and RL, respectively).

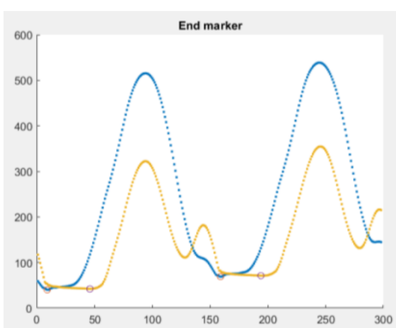
Therefore, a Full-Body Lumbar Spine model was used (FBLS) (https://simtk.org/projects/fullbodylumbar/) (Figure 6). The FBLS model was developed based on three previous models and consists of a detailed trunk musculature and degrees of freedom in the lumbar spine and lower extremities. The model's validation was done through a jogging protocol. (Raabe et al., 2016)

Figure 6 Full Body Musculoskeletal model of the lumbar spine (FBLS) (Extracted from Raabe et al.,2016).

The trunk kinematics were converted from radians to degrees. The model was scaled for each participant based on their anthropometrics, then the inverse kinematics tool was used to estimate lower limb, trunk, and pelvic kinematics.

Considering those kinematics variables and knowing that the most prominent asymmetry might occur during the stance phase, we firstly identified the running stance phase as the period from heel strike to pre-toe off. After that, the data was extracted at the peak knee flexion at midstance (flat foot) (Figure 7). Considering this, we decided to look at the functional tests also based on the peak knee flexion angle from the leg of interest, except for the step-hurdle, in which we extracted the data from the stationary leg based on the maximum knee flexion of the moving leg. The data were processed and analyzed with customed-made scripts written in MATLAB, 2021a. The outcome was divided in test, stride, running lap, and side. Given the possible variability and asymmetry between limbs, left and right leg were analysed independently. Due to poor consistency in the kinematic, two subjects were excluded from the analysis (S05 and S12), which resulted in N=10 used in the results reported below.

A



B

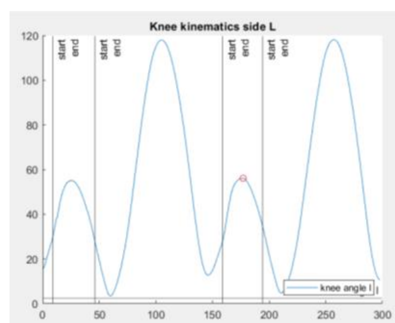


Figure 7. Running trials and data of interest. A. Circles identify heel and toe contact; B. Start and end of stance phase, and circle identify peak knee flexion.

5.4 Statistical analysis

Firstly, all kinematic measures (pelvic tilt, pelvic list, pelvic rotation, trunk rotation, lateral bending, and axial rotation) were subtracted by their corresponding static pose values for each subject. A descriptive analysis of the characteristics of the participants was performed. Then, the average across repeated measures (strides in running and trials in other tests) was computed for statistical analysis. Thirdly, the effect of side and running laps on the kinematic measures was assessed using a two-way analysis of variance (ANOVA). A second two-way ANOVA was applied to assess the effect of side and type of functional tests on the kinematic measures using only the first running lap. The normality of the model residuals was inspected with histograms and Q-Q plots. Post-hoc estimated marginal means was applied for multiple comparisons when necessary. Lastly, based on the means a Pearson correlation analysis was performed between running and functional tests for each side. Level of significance was set at 5%. All statistical analysis were performed using SPSS (Version 28; IBM Corporation, Armonk, NY, USA). The results of the trunk, pelvic and hip kinematics during running and functional tests are presented as means and ± standard deviation.

6 Results

Results of the 10 recreational runners, and their running and functional tests kinematics are presented as means ± standard deviation for each side, test, running laps, and stride. The kinematic values of the running represent 2 strides for each leg every 5 minutes during the trial (total 40 minutes). A color was set for each subject. Subjects were right leg dominant, except S2 and S3.

The average running speed was 3.26 m/s (Sd ± 0,48), and the data showed very consistent speed throughout the 40 minutes. The height data from the CMJ has shown that the protocol was a non-exhausting running protocol, where subjects improved their jump-height after the protocol, pre-29,2cm±4,9cm and pos 32,5±4,6cm.

Trunk kinematics can be seen in figure 8, where axial rotation and lateral bending use the stance leg as a reference, so positive values refer to ipsilateral trunk movements (shoulder forward) and negative values contralateral. Axial rotation is plotted in figure 8a and is expected to be around zero. Our data shows slight changes in the axial rotation for 40 minutes running, and subjects presented slightly contralateral and ipsilateral rotation, as LL (-.02±.228) and RL (0.38±.225) respectively, but no significant differences between sides. Although the lateral bending (Figure 8b) presented similar pattern for each step throughout the trial, it showed a opposite kinematic between sides, thus a significant difference between LL and RL [$F(1,38) = [390.89]$, $p<,001$] demonstrating that subjects tend to lean ipsilaterally and contralaterally when RL and LL stride (-.20±.07 and .19±.13), respectively.

The hip kinematics can be seen in Figures 9 a, b and c. Based on the data, subjects presented similar and symmetrical flexion pattern throughout the 40-minute run, 24.44±16.87 and 23.04±16.13 for LL and RL, correspondingly. Similar adduction pattern was observed in both steps and sides; however, the LL steps presented a slightly bigger adduction angles (13.82± 11.52) compared to the RL (3.95±2.83) (Figure 9b). The mean hip rotation for the RL varied from 3.72±4.09 and it was characterized by a discrete difference compared to the LL (4.40±3.02). Except subjects 01, 02 and 11 (S01, S02 and S11), all subjects presented an internal rotation during the midstance.

The last sequence of graphs refers to pelvic kinematics (Figure 11), where the stance leg is the reference; thus, positive values refer to ipsilateral movement. The pelvic list is a synonym for pelvic drop (Figure 10a); there was a significant difference between sides [F (1,38) = [168.693], p<0.001], where RL presented contralateral drop and LL ipsilateral drop. There was a significant difference between pelvic rotation from LL and RL [F (1, 38) = 22.884, p<0.001], where in LL stance the ipsilateral rotation (left ASIS forward) for all subjects, and RL varied from contra to ipsilateral rotations, but no difference between strides nor laps (Figure 10b). Lastly, pelvic tilt presented a similar pattern within and between laps and subjects, where positive values refer to posterior tilt and negative to anterior tilt (LL: -5.03±7.07, RL: -3.74±6.48), where most of the subjects presented an anterior tilt (Figure 10c).

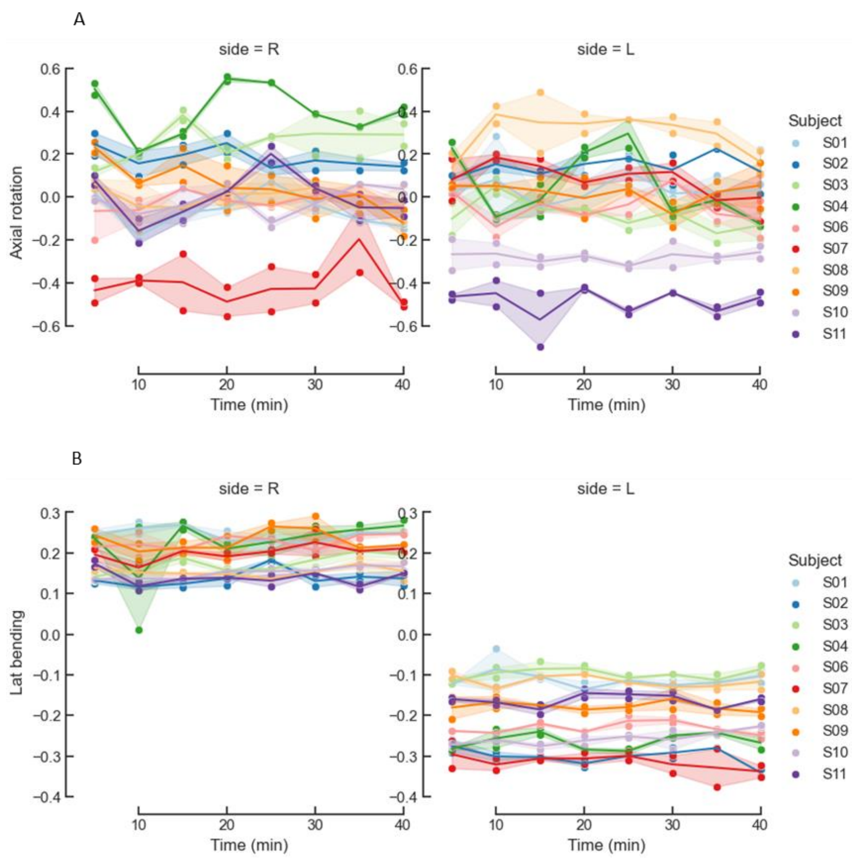


Figure 8. Trunk kinematics running: A. Axial rotation, B. Lateral bending. The shaded area represents the difference between each step within 1 stride.

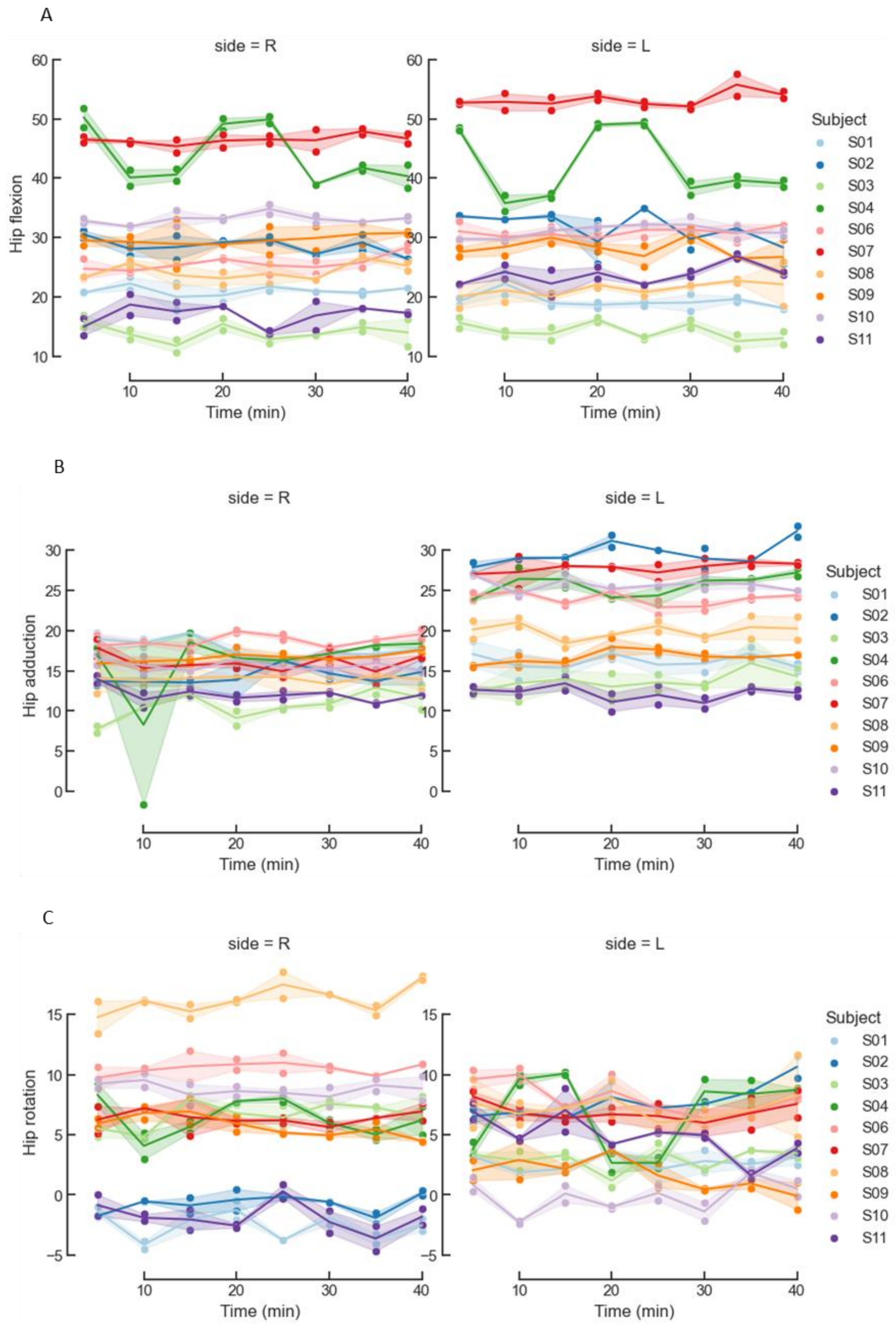


Figure 9. Hip kinematics running: A. Hip flexion and extension; B. Hip adduction and abduction; C. Hip internal and external rotation

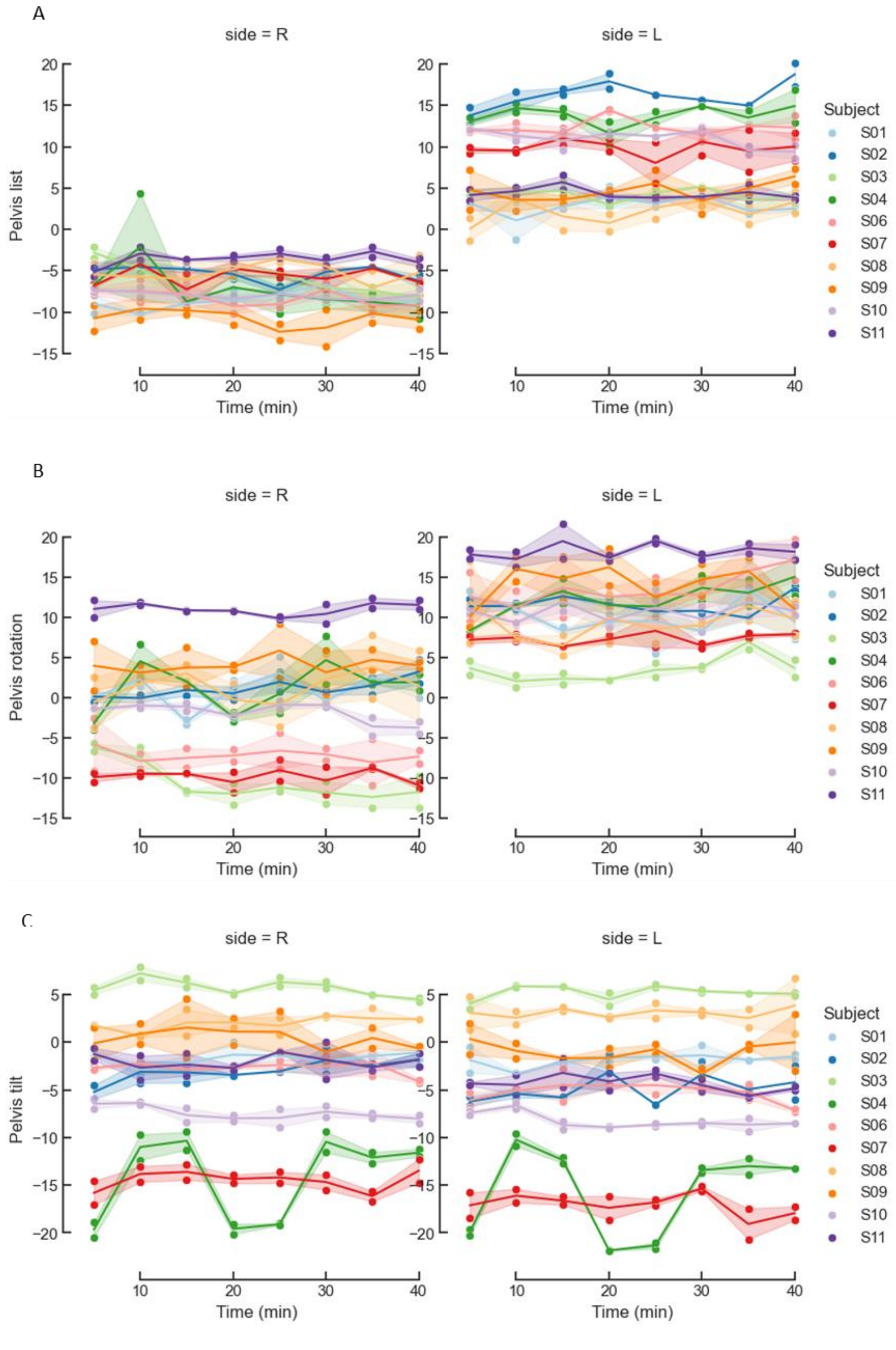


Figure 10. Pelvic kinematics running: A. Pelvic tilt; B. Pelvic rotation; C. Pelvic tilt.

It is interesting to note that most subjects maintained similar movement pattern or control along the 40 minutes, which clearly shows that subjects were in their comfortable pace. A two-way ANOVA revealed that there was not a statistically significant interaction between lap for all kinematic variable of interest. Thus, for the following results (running x functional tests), only lap 1 was taken into account.

The mean joint angles for the functional tests and running are presented in Figure 11. The effect of side was significant on the pelvic list and lateral bending, which showed differences within all tests except squat: and squat and step, respectively (Table 2b). When comparing the effect of test vs. test (run vs tests) on the dependent kinematic variables, pelvic tilt demonstrated a significant difference between tests, except lunge; and axial rotation for all tests, except squat (Table 2c). Moreover, a significant interaction effect of side vs. test was observed in lateral bending, pelvic rotation, and pelvic list (Table 2a); lateral bending bilateral differences for squat and step; pelvic list was bilateral difference for squat and only for RL SLS; and lastly the pelvic rotation difference was observed bilaterally for squat and step, and only for LL lunge. Trunk, hip and knee flexion-extension were similar between sides, as expected considering the differences between tests.

Table 2.Pairwise comparations (p-values) of kinematic measures between tests and sides. A: Test vs Side, where orange stand for left and blue for right; B: Side vs side; C: Test vs test

A

Tests x Sides	***Lateral bending***	***Pelvic list***	***Pelvic rotation***
	Run	**Run**	**Run**
Squat	**<,001**	<,001	**.001**
Lunge	.708	.512	**<,001**
SLS	.069	.077	**.023**
Step	**<,001**	.113	**<,001**
Squat	**<,001**	**.004**	**.003**
Lunge	0,624	.929	**.010**
SLS	0,108	**.025**	.390
Step	**<,001**	.270	**<,001**

B

Side x Side	*Lateral bending*	*Pelvic list*
Run	**<,001**	**<,001**
Squat	0,91	.934
Lunge	**<,001**	**<,001**
Sls	**<,001**	**.018**
Step	**0.42**	**<,001**

C

Test x Test	*Pelvic tilt*	*Axial rotation*
	run	**run**
Squat	**<,001**	**<,001**
Lunge	.229	.503
SLS	**<,001**	.439
Step	**<,001**	.134

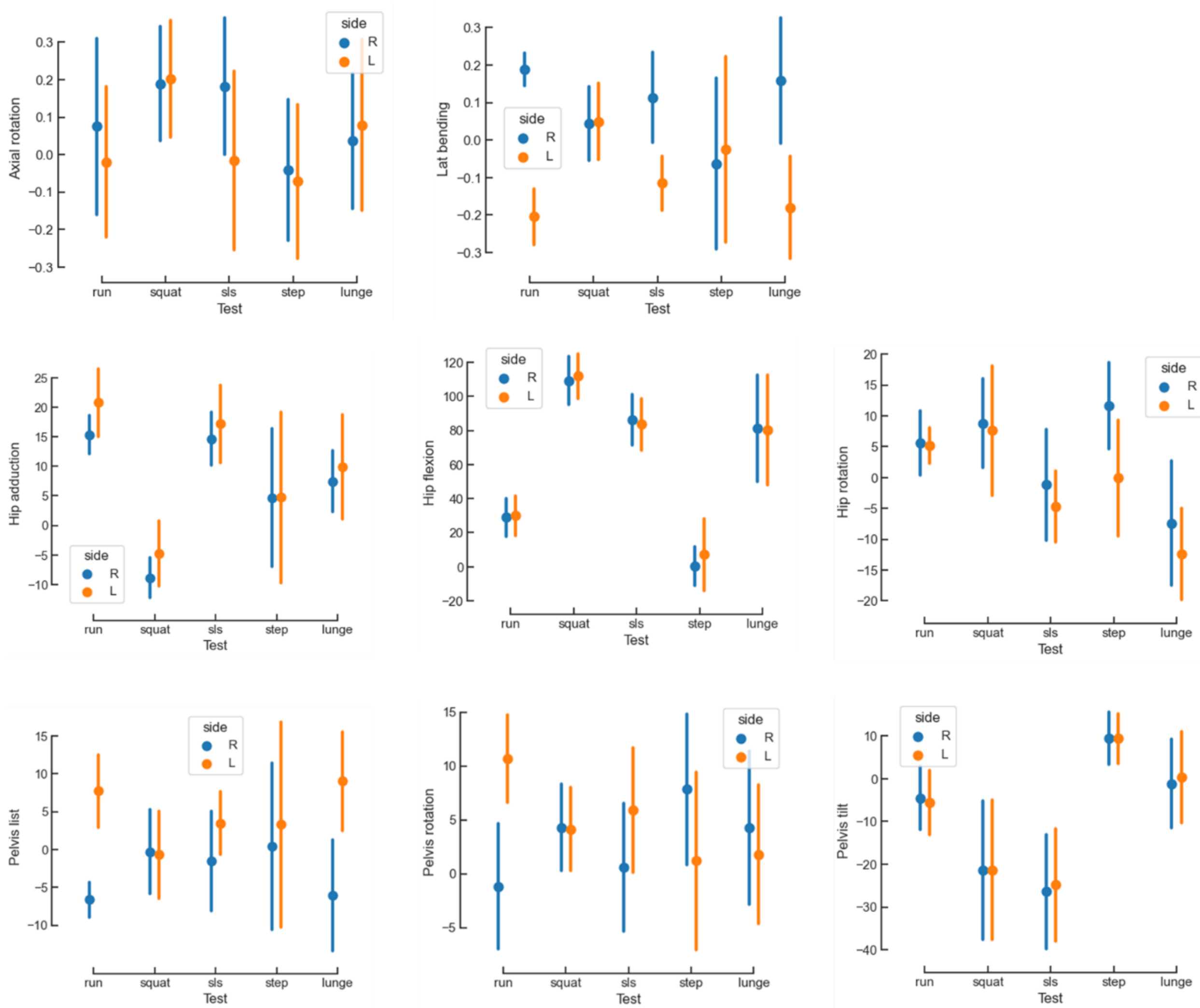


Figure 11. Kinematic mean values among running and tests, where orange stands for left leg and blue for right leg.

The Pearson correlation coefficient was computed to assess the relationship between kinematic variables during running and functional tests (Table 3).

Pelvic tilt presented a significant positive linear relationship for most of the tests, varying from moderate to strong correlations; LL squat (r=.675, p < .05) and RL squat (r=.677, p < .05), LL lunge (r=.651 and .641, p < .05) and RL lunge (r=.755 and 754, p < .05), LL SLS (r=.653, p < .05) and RL SLS (r=.733 and .697, p < .05), and LL step (r=.707 and .674, p < .05). Surprisingly, pelvic list did show either a weak positive or negative correlation in most of the conditions. Pelvic rotation demonstrated a strong to weak correlations; LL squat (*r*=.745 and .667, $p < .05$) and RL squat (*r*=-.809 and .700, p < .05); RL lunge (*r*=-.690, $p < .05$); LL SLS (*r*=.781, $p < .05$) and RL SLS (*r*=.719, $p < .05$); LL step (*r*=-.690, $p < .05$) and RL step (*r*=.706 and .724, $p < .05$)

Axial rotation had just two positive significant correlation for LL run and squat- LL and RL (*r*=.785 and .764, $p < .05$), other values were weak to moderate and negative correlations. Lastly, the lateral bending presented weak (negative and positive values) correlations for all variables.

Table 3. Pearson correlations between means of running and functional test

		Left	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*
		Squat	**Squat**	**Lunge**	**Lunge**	**SLS**	**SLS**	**Step**	**Step**
Pelvic Tilt	Run Left	**.675***	**.677***	**.651***	**.755***	**.655***	**.733***	**.707***	0.082
	Run Right	0.663	0.666	**.641***	**.754****	0.599	**.697***	**674***	0.094
Pelvic List	Run Left	0.666	0.659	0.228	0.216	0.043	-.688	0.032	-0.177
	Run Right	-0.095	-0.107	0.526	-0.474	-0.500	-0.045	-0.046	0.438
Pelvic Rotation	Run Left	**.745***	**.809***	0.389	0.455	**.781***	0.528	0.584	**.706***
	Run Right	**.667***	**.700***	0,313	**.690***	0.601	**.719***	**.690***	**.724***
Axial Rotation	Run Left	**.785***	**.764***	-0,111	0.456	0.466	0.351	0.566	0.127
	Run Right	0.246	0.232	-0.016	0.366	0.132	0.097	0.420	-0.161
Lateral Bending	Run Left	0.460	0.460	-0.191	0.422	-0.181	0.146	0.008	-0.241
	Run Right	-0.142	-0.132	0.346	-0.134	0.047	-0.117	0.077	0.266

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

7 Discussion

The purpose of this thesis was to assess the trunk and lumbo-pelvic kinematics during a non-exhausting 40 minutes run and functional tests. The results reveal that kinematics maintained similar pattern throughout the running protocol, with a few and slightly interlimb differences. In the same line, the functional tests presented similar pattern, a significant interlimb asymmetries were observed on lateral bending and pelvic list for the majority of tests, and lastly, the correlation analysis varied from weak to strong among tests and sides.

The first finding confirmed our first hypothesis (H1) that a 40minutes run at a self-selected pace would not alter the kinematics in recreational runners but would show subtle interlimb differences. We believe that kinematics did not significantly change because subjects had had enough running experience and ran at their comfortable pace.

Despite the similar lower limb kinematics throughout the protocol, subjects presented a few inter-limbs kinematics asymmetries in some of the parameters (Pelvic list and rotation, and lateral bending). It is assumed that healthy subjects have symmetrical gait; however, a growing body of evidence indicates that kinematic asymmetries exist(Schache et al., 2001). Among many variables, we believe that limb asymmetry could be caused by running experience or leg dominance. Even though subjects had over one year of running experience, some had more than ten years of practice, which could explain why some subjects presented a symmetrical movement pattern. Studies have demonstrated that more experienced and competitive runners produce more symmetrical interlimb kinematics regardless of the speed due to motor control and experience (Carpes et al., 2010; Clermont et al., 2017, 2019; Nakayama et al., 2010). In addition, our kinematics in all planes during midstance corroborates with previous studies with recreational runners and similar speed. Schade and colleagues evaluated the lumbar spine and pelvis kinematics during running; midstance was marked by lumbar ipsilateral lateral bend, contralateral axial rotation and slightly extended; pelvis demonstrated a contralateral pelvic drop, ipsilateral rotation and anterior tilt. They noted a strong negative correlation between lumbar flexion/extension and tilt, and lateral bending and pelvic drop. (Schache et al., 2002)

Other two studies comparing lowerlimb and pelvic kinematic in competitive and recreational, and higher- lower mileage runners have shown that midstance was marked by anterior pelvic tilt, ipsilateral pelvic rotation, and contralateral pelvic drop, and hip adduction and internal rotation(Clermont et al., 2017, 2019). Similarly, Preece and peers found same similar kinematic patterns (Preece et al., 2016).

Laterality was thought to be a possible reason for limb asymmetries, however previous studies on running and drop-landing suggest that asymmetries are not related to leg dominance(Brown et al., 2014; Carpes et al., 2010). Asymmetry is expected to happen, nonetheless can be a relevant factor if too discrepant during cyclic and prolonged activity, which can overload the musculoskeletal system, leading to injury (Radzak et al., 2017).

Exercise intensity and duration can induce fatigue. Fatigue is a multi-factorial phenomenon that negatively affects the capacity to generate power, altering the neuromuscular control, biomechanical (kinematics and kinetics) and electromyographic parameters, thus leading to poor performance (Apte et al., 2021; Brown et al., 2014; Enoka & Duchateau, 2008). Recent studies have shown that exhausting running protocols (treadmill and overground) have altered pelvic, ankle, hip and knee control; the pelvis presented an increased range of movement for rotation and anterior tilt, increased hip kinematics in all planes, and an altered pelvic trunk coupling control (Apte et al., 2021; Willwacher et al., 2020). Moreover, more studies have proven that trunk and lower limb mechanic change according to the speed in recreational runners, highlighting the importance of “self-selected pace” when analysing individual biomechanics (Clermont et al., 2017, 2019; Orendurff et al., 2018; Preece et al., 2016).

Each functional test and running require a different level of motor control, representing a progression of a movement that increasingly challenges the lumbopelvic and hip control. We hypothesized that activities with wider and stable stances, such as squat and lunge, would show less lumbopelvic and interlimb kinematic variation than single-stance movements, such as running or SLS. Contrary to our second hypothesis, interlimb asymmetries were only observed on lateral bending and pelvic list for all tests, except the squat (side vs. side analysis). The literature lacks studies that analyze left and right pelvis separately; but, similarly to our results, Lewis and peers found that during maximum peak knee flexion during SLS, the pelvis tilts anteriorly and the trunk ipsilaterally flexes (Lewis et al., 2015). We believe that the asymmetries might be caused either by biomechanical differences or muscle unbalance, especially in the core and hip muscles.

Contrary to our hypothesis (H3), the correlation analysis varied grandly between tests and running; and the strongest correlations were during wider stances and stability. Contrary to our findings, Whatman and colleagues analyzed the correlation between jogging and five functional tests, including the SLS, lunge and single leg step, and found that pelvic tilt and rotation presented a moderate to strong correlation (r= 0.59 to 0.71), and trunk lateral flexion and rotation weak correlation (r= 0.09 to 0.40); strong correlation were observed for ankle, knee and hip parameters(Whatman et al., 2011). Similarly, to the previous study, Schreiber (2020) found that single-leg step down had a moderate to strong correlation with running in healthy subjects(Schreiber & Becker, 2020). The previous authors support the use these functional tests as screening tool for lower limb kinematics in runners, however based on our study caution might be taken.

This study has several limitations that could be improved and included in future studies. Firstly, to include the upper limb during the 3D- analysis because it is known that arm motion acts as a counterbalance during running, which alters the trunk control (Preece et al., 2016); secondly, considering all the biomechanical differences between genders, it would be interesting to analyze the kinematic based on gender instead of only running experience. Thirdly, even though we had collected the EMG signals of the gluteus maximum and medium, it was not used for analyses; moreover, this study missed the strength assessment of the core and gluts, and lower limb and lumbar flexibility, which would have contributed to understanding the interlimb asymmetries. Lastly, limiting the peak knee flexion during the functional tests based on the ROM during running, generating more comparable parameters (Alenezi et al., 2016; Preece et al., 2016; Schreiber & Becker, 2020; Whatman et al., 2011). Another important limitation is the possible skin movement during all dynamic trials, which might alter the position of the markers.

To our understanding, this is the first study with this protocol. Despite some limitations, this study has several strengths; primarily, it is one of a few studies conducted in a track and field, where subjects could run in their natural “habitat” and pace, thus minimal interference with unfamiliar surfaces. Along with, this is one of the unique studies with prolonged running protocol in track and field. Besides, even with all possible interference and artefacts, the majority of data collected was considered good quality (10 out of 12 subjects). Even though there is extensive literature on running biomechanics and running-related injuries, the literature on interlimb kinematic and trunk and lumbopelvic control during functional tests and running has received very little attention. Moreover, the existing studies presented different or poor methodologies, which limits the search and interferes when comparing the results. On the other hand, there is enough evidence showing the importance of lumbopelvic control on cyclic sports activities and their running-related injuries(Schache et al., 2002). More importantly, this thesis brings a new understanding on lumbopelvic control during self-selected pace running and functional tests for clinical and practical use. It also emphasizes the importance of better understanding their relationship during such activities and need for future studies on the topic.

8 Conclusion

Each individual has a specific anatomy and biomechanical pattern, which makes locomotion and motor control so fascinating. Even though we must respect its individuality, we acknowledge that there are many similarities between individuals, which are considered the normality among groups with similar characteristics. Moreover, when studying biomechanics, it's important to respect the subject's natural locomotion pattern.

To conclude, the 3D analysis during the maximum peak knee flexion during midstance of a self-selected pace running and functional tests in recreational runners presented a very similar trunk, lumbopelvic and hip biomechanical pattern; and even with all similarities, some subjects have had some subtle asymmetries. A significant interlimb asymmetry was observed during running only for pelvic list, pelvic rotation and lateral bending. The analyse of side effect on the measures were observed for lateral bending and pelvic list (run, SLS and lunge); the major differences when analysing the interaction effect on run x test was only observed for pelvic tilt (squat, SLS and step) and axial rotation (squat). Lastly, the major difference side x test (test x run) was shown in pelvic rotation (squat, step and lunge), pelvic list (squat and SLS), and lateral bending (squat and step).

There were a positive, moderate to strong correlations only for pelvic tilt and rotation among running and functional tests. Even though, the functional tests have similar visual movement pattern, based on our results, these functional tests should be applied as part of broader screening tests, thus clinical decisions should not rely only on them. Emphasizing the importance of specificity when assessing runners. Considering this, further research is needed to investigate the correlation of trunk and lumbopelvic kinematics between functional tests and running.

9 References

1 Aderem, J., & Louw, Q. A. (2015). Biomechanical risk factors associated with iliotibial band syndrome in runners: A systematic review. BMC Musculoskeletal Disorders, 16(1), 356. doi:10.1186/s12891-015-0808-7

2 Agresta, C., Slobodinsky, M., & Tucker, C. (2014). Functional movement ScreenTM – normative values in healthy distance runners. International Journal of Sports Medicine, 35(14), 1203-1207. doi:10.1055/s-0034-1382055

3 Alenezi, F., Herrington, L., Jones, P., & Jones, R. (2016). How reliable are lower limb biomechanical variables during running and cutting tasks. Journal of Electromyography and Kinesiology, 30, 137–142. https://doi.org/10.1016/j.jelekin.2016.07.001

4 Apte, S., Prigent, G., Stöggl, T., Martínez, A., Snyder, C., Gremeaux-Bader, V., & Aminian, K. (2021). Biomechanical Response of the Lower Extremity to Running-Induced Acute Fatigue: A Systematic Review. In Frontiers in Physiology (Vol. 12). Frontiers Media S.A. https://doi.org/10.3389/fphys.2021.6460423.

5 Australian bureau of statistics. (2010). (No. 17). doi:10.1016/S1542-3565(19)30794-3 Retrieved from https://www.clinicalkey.es/playcontent/1-s2.0-S1542356519307943

6 Brown, A. M., Zifchock, R. A., & Hillstrom, H. J. (2014). The effects of limb dominance and fatigue on running biomechanics. Gait and Posture, 39(3), 915–919. https://doi.org/10.1016/j.gaitpost.2013.12.007

7 Buist, I., Bredeweg, S. W., Lemmink, Koen A. P. M, van Mechelen, W., & Diercks, R. L. (2010). Predictors of running-related injuries in novice runners enrolled in a systematic training program A prospective cohort study. American Journal of Sports Medicine, 38(2), 273-280. doi:10.1177/0363546509347985

8 Bushman, T. T., Grier, T. L., Canham-Chervak, M., Anderson, M. K., North, W. J., & Jones, B. H. (2016). The functional movement screen and injury risk. The American Journal of Sports Medicine, 44(2), 297-304. doi:10.1177/0363546515614815

9 Carpes, F. P., Mota, C. B., & Faria, I. E. (2010). On the bilateral asymmetry during running and cycling - A review considering leg preference. In Physical Therapy in Sport (Vol. 11, Issue 4, pp. 136–142). https://doi.org/10.1016/j.ptsp.2010.06.005

10 Ceyssens, L., Vanelderen, R., Barton, C., Malliaras, P., & Dingenen, B. (2019). Biomechanical Risk Factors Associated with Running-Related Injuries: A Systematic Review. In Sports Medicine (Vol. 49, Issue 7, pp. 1095–1115). Springer International Publishing. https://doi.org/10.1007/s40279-019-01110-z

11 Chimera, N. J., & Warren, M. (2016). Use of clinical movement screening tests to predict injury in sport. World Journal of Orthopedics, 7(4), 202-217. doi:10.5312/wjo.v7.i4.202

12 Clermont, C. A., Phinyomark, A., Osis, S. T., & Ferber, R. (2019). Classification of higher- and lower-mileage runners based on running kinematics. Journal of Sport and Health Science, 8(3), 249-257. doi:10.1016/j.jshs.2017.08.003

13 Clermont, C. A., Osis, S. T., Phinyomark, A., & Ferber, R. (2017). Kinematic gait patterns in competitive and recreational runners. Journal of Applied Biomechanics, 33(4), 268–276. https://doi.org/10.1123/jab.2016-0218

14 Cook, G., Burton, L., & Hoogenboom, B. (2006a). Pre-participation screening: The use of fundamental movements as an assessment of function - part 1. North American Journal of Sports Physical Therapy, 1(2), 62-72. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/21522216

15 Cook, G., Burton, L., & Hoogenboom, B. (2006b). Pre-participation screening: The use of fundamental movements as an assessment of function - part 2. North American Journal of Sports Physical Therapy, 1(3), 132-139. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/21522225

16 Cook, G., Burton, L., Hoogenboom, B. J., & Voight, M. (2014a). Functional movement screening: The use of fundamental movements as an assessment of function - part 1. International Journal of Sports Physical Therapy, 9(3), 396-409. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/24944860

17 Cook, G., Burton, L., Hoogenboom, B. J., & Voight, M. (2014b). Functional movement screening: The use of fundamental movements as an assessment of function-part 2. International Journal of Sports Physical Therapy, 9(4), 549-563. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/25133083

18 Crossley, K. M., Zhang, W. J., Schache, A. G., Bryant, A., & Cowan, S. M. (2011). Performance on the single-leg squat task indicates hip abductor muscle function.

American Journal of Sports Medicine, 39(4), 866–873. https://doi.org/10.1177/0363546510395456

19 DeLeo, A. T., Dierks, T. A., Ferber, R., & Davis, I. S. (2004). Lower extremity joint coupling during running: A current update. Clinical Biomechanics, 19(10), 983–991. https://doi.org/10.1016/j.clinbiomech.2004.07.005

20 de Oliveira, R. R., Chaves, S. F., Lima, Y. L., Bezerra, M. A., Leão Almeida, G. P., & de Paula Lima, Pedro Olavo. (2017a). There are no biomechanical differences between runners classified by the functional movement screen. International Journal of Sports Physical Therapy, 12(4), 625-633. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/28900569

21 de Oliveira, R. R., Chaves, S. F., Lima, Y. L., Bezerra, M. A., Leão Almeida, G. P., & de Paula Lima, Pedro Olavo. (2017b). There are no biomechanical differences between runners classified by the functional movement screen. International Journal of Sports Physical Therapy, 12(4), 625-633. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/28900569

22 Dierks, T. A., Davis, I. S., & Hamill, J. (2010). The effects of running in an exerted state on lower extremity kinematics and joint timing. Journal of Biomechanics, 43(15), 2993–2998. https://doi.org/10.1016/j.jbiomech.2010.07.001

23 Dugan, S. A., & Bhat, K. P. (2005). Biomechanics and analysis of running gait. In Physical Medicine and Rehabilitation Clinics of North America (Vol. 16, Issue 3, pp. 603–621). https://doi.org/10.1016/j.pmr.2005.02.007

24 Dye, S. F. (2005). The pathophysiology of patellofemoral pain: A tissue homeostasis perspective. Clinical Orthopaedics and Related Research, (436), 100-110. doi:10.1097/01.blo.0000172303.74414.7d

25 Ferber, R., & Macdonald, S. L. (2014). Running mechanics and gait analysis. Champaign, IL: Human Kinetics. Retrieved from http://bvbr.bib-bvb.de:8991/F?func=service&doc_library=BVB01&local_base=BVB01&doc_number=027593476&sequence=000004&line_number=0001&func_code=DB_RECORDS&service_type=MEDIA

26 Fields, K. B., Sykes, J. C., Walker, K. M., & Jackson, J. C. (2010). Prevention of running injuries. Current Sports Medicine Reports, 9(3), 176-182. doi:10.1249/jsr.0b013e3181de7ec5

27 Franke, T. P. C., Backx, F. J. G., & Huisstede, B. M. A. (2019). Running themselves into the ground? incidence, prevalence, and impact of injury and illness in runners preparing for a half or full marathon. The Journal of Orthopaedic and Sports Physical Therapy, 49(7), 518-528. doi:10.2519/jospt.2019.8473

28 Frohm, A., Heijne, A., Kowalski, J., Svensson, P., & Myklebust, G. (2012). A nine-test screening battery for athletes: A reliability study. Scandinavian Journal of Medicine & Science in Sports, 22(3), 306-315. doi:10.1111/j.1600-0838.2010.01267.x

29 Frost, D., Beach, T., Callaghan, J., & McGill, S. (2012). Using the functional movement screen™ to evaluate the effectiveness of training. Journal of Strength and Conditioning Research, 26(6), 1620-1630. doi:10.1519/JSC.0b013e318234ec59

30 Gaur, A., & Gaur, S. (2012). Summarizing Data: Descriptive Statistics. In Statistical Methods for Practice and Research: A Guide to Data Analysis Using SPSS (pp. 37–51). SAGE Publications India Pvt Ltd. https://doi.org/10.4135/9788132108306.n3

31 Gray, H. A., Guan, S., Thomeer, L. T., Schache, A. G., de Steiger, R., & Pandy, M. G. (2019). Three-dimensional motion of the knee-joint complex during normal walking revealed by mobile biplane x-ray imaging. Journal of Orthopaedic

32 Helen Clay, MS, LAT, ATC Jamie Mansell, LAT, ATC Ryan Tierney. ATC.Association between rowing injuries and the functional movement screentm in female collegiate division i rowers

33 Hespanhol Junior, L. C., van Mechelen, W., Postuma, E., & Verhagen, E. (2016). Health and economic burden of running-related injuries in runners training for an event: A prospective cohort study. Scandinavian Journal of Medicine & Science in Sports, 26(9), 1091-1099. doi:10.1111/sms.12541

34 Hotta, T., Nishiguchi, S., Fukutani, N., Tashiro, Y., Adachi, D., Morino, S., . . . Aoyama, T. (2015). Functional movement screen for predicting running injuries in 18- to 24-year-old competitive male runners. Journal of Strength and Conditioning Research, 29(10), 2808-2815. doi:10.1519/JSC.0000000000000962

35 Ida Buist, Steef W. Bredeweg, Willem van Mechelen, Koen A. P. M. Lemmink, Gert-Jan Pepping, & Ron L. Diercks. (2008). No effect of a graded training program on the number of running-related injuries in novice runners. The American Journal of Sports Medicine, 36(1), 33-41. doi:10.1177/0363546507307505

36 Kiesel, K., Plisky, P. J., & Voight, M. L. (2007). Can serious injury in professional football be predicted by a pre-season functional movement screen? North American Journal of Sports Physical Therapy, 2(3), 147-158. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/21522210

37 Koblbauer, I. F., van Schooten, K. S., Verhagen, E. A., & van Dieën, J. H. (2014). Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. Journal of Science and Medicine in Sport, 17(4), 419–424. https://doi.org/10.1016/J.JSAMS.2013.05.013

38 Kozanek, M., Hosseini, A., Liu, F., van de Velde, S. K., Gill, T. J., Rubash, H. E., & Li, G. (2009). Tibiofemoral kinematics and condylar motion during the stance phase of gait. Journal of Biomechanics, 42(12), 1877–1884. https://doi.org/10.1016/j.jbiomech.2009.05.003

39 Lewis, C. L., Foch, E., Luko, M. M., Loverro, K. L., & Khuu, A. (2015). Differences in lower extremity and trunk kinematics between single leg squat and step down tasks. PLoS ONE, 10(5). https://doi.org/10.1371/journal.pone.0126258

40 Linton, L., & Valentin, S. (2018). Running with injury: A study of UK novice and recreational runners and factors associated with running related injury. Journal of Science and Medicine in Sport, 21(12), 1221-1225. doi:10.1016/j.jsams.2018.05.021

41 Lloyd, R. S., Oliver, J. L., Radnor, J. M., Rhodes, B. C., Faigenbaum, A. D., & Myer, G. D. (2014). Relationships between functional movement screen scores, maturation and physical performance in young soccer players. Journal of Sports Sciences, 33(1), 11-19. doi:10.1080/02640414.2014.918642

42 Loudon, J. K., Parkerson-Mitchell, A. J., Hildebrand, L. D., & Teague, C. (2014). Functional movement screen scores in a group of running athletes. Journal of Strength and Conditioning Research, 28(4), 909-913. doi:10.1097/jsc.0000000000000233

43 Lun, V., Meeuwisse, W. H., Stergiou, P., & Stefanyshyn, D. (2004). Relation between running injury and static lower limb alignment in recreational runners. British Journal of Sports Medicine, 38(5), 576-580. doi:10.1136/bjsm.2003.005488

44 Minick, K., Kiesel, K., Burton, L., Taylor, A., Plisky, P., & Butler, R. (2010). Interrater reliability of the functional movement screen. Journal of Strength and Conditioning Research, 24(2), 479-486. doi:10.1519/JSC.0b013e3181c09c04

45 Mokha, M., Sprague, P. A., & Gatens, D. R. (2016). Predicting musculoskeletal injury in national collegiate athletic association division II athletes from asymmetries and individual-test versus composite functional movement screen scores. Journal of Athletic Training, 51(4), 276-282. doi:10.4085/1062-6050-51.2.07

46 Moore, E., Chalmers, S., Milanese, S., & Fuller, J. (2019). Factors influencing the relationship between the functional movement screen and injury risk in sporting populations: A systematic review and meta-analysis. Sports Medicine, 49(9), 1449-1463. doi:10.1007/s40279-019-01126-5

47 Moran, R. W., Schneiders, A. G., Mason, J., & Sullivan, S. J. (2017). Do functional movement screen (FMS) composite scores predict subsequent injury? A systematic review with meta-analysis. British Journal of Sports Medicine, 51(23), 1661-1669. doi:10.1136/bjsports-2016-096938

48 Mottram, S., & Comerford, M. (2007). A new perspective on risk assessment. Physical Therapy in Sport, 9(1), 40-51. doi:10.1016/j.ptsp.2007.11.003

49 Nakayama, Y., Kudo, K., & Ohtsuki, T. (2010). Variability and fluctuation in running gait cycle of trained runners and non-runners. Gait and Posture, 31(3), 331–335. https://doi.org/10.1016/j.gaitpost.2009.12.003

50 Nicola, T. L., & Jewison, D. J. (2012). The Anatomy and Biomechanics of Running. In Clinics in Sports Medicine (Vol. 31, Issue 2, pp. 187–201). https://doi.org/10.1016/j.csm.2011.10.001

51 Nielsen, R. O., Buist, I., Parner, E. T., Nohr, E. A., Sørensen, H., Lind, M., & Rasmussen, S. (2013). Predictors of running-related injuries among 930 novice runners. Orthopaedic Journal of Sports Medicine, 1(1), 2325967113487316. doi:10.1177/2325967113487316

52 Nielsen, R. O., Buist, I., Sørensen, H., Lind, M., & Rasmussen, S. (2012). Training errors and running related injuries: A systematic review. International Journal of Sports

Physical Therapy, 7(1), 58-75. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/22389869

53 Novacheck, T. F. (1998). The biomechanics of running. Gait & Posture, 7(1), 77-95. doi:10.1016/s0966-6362(97)00038-6

54 O'Connor, F. G., Deuster, P. A., Davis, J., Pappas, C. G., & Knapik, J. J. (2011). Functional movement screening: Predicting injuries in officer candidates. Medicine and Science in Sports and Exercise, 43(12), 2224-2230. doi:10.1249/MSS.0b013e318223522d

55 Ooms, L., Veenhof, C., & de Bakker, D. H. (2013). Effectiveness of start to run, a 6-week training program for novice runners, on increasing health-enhancing physical activity: A controlled study. BMC Public Health, 13(1), 697. doi:10.1186/1471-2458-13-697

56 Orendurff, M. S., Kobayashi, T., Tulchin-Francis, K., Tullock, A. M. H., Villarosa, C., Chan, C., & Strike, S. (2018). A little bit faster: Lower extremity joint kinematics and kinetics as recreational runners achieve faster speeds. Journal of Biomechanics, 71, 167–175. https://doi.org/10.1016/j.jbiomech.2018.02.010

57 Postolka, B., Schütz, P., Fucentese, S. F., Freeman, M. A. R., Pinskerova, V., List, R., & Taylor, W. R. (2020). Tibio-femoral kinematics of the healthy knee joint throughout complete cycles of gait activities. Journal of Biomechanics, 110. https://doi.org/10.1016/j.jbiomech.2020.109915

58 Preece, S. J., Mason, D., & Bramah, C. (2016). The coordinated movement of the spine and pelvis during running. Human Movement Science, 45, 110–118. https://doi.org/10.1016/j.humov.2015.11.014

59 Radzak, K. N., Putnam, A. M., Tamura, K., Hetzler, R. K., & Stickley, C. D. (2017). Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. Gait and Posture, 51, 268–274. https://doi.org/10.1016/j.gaitpost.2016.11.005

60 Ressman, J., Grooten, W. J. A., & Rasmussen Barr, E. (2019). Visual assessment of movement quality in the single leg squat test: A review and meta-analysis of inter-rater and intrarater reliability. BMJ Open Sport & Exercise Medicine, 5(1), e000541. doi:10.1136/bmjsem-2019-000541

61 Samitz, G., Egger, M., & Zwahlen, M. (2011). Domains of physical activity and all-cause mortality: Systematic review and dose–response meta-analysis of cohort studies. International Journal of Epidemiology, 40(5), 1382-1400. doi:10.1093/ije/dyr112

62 Saragiotto, B. T., Yamato, T. P., & Lopes, A. D. (2014). What do recreational runners think about risk factors for running injuries? A descriptive study of their beliefs and opinions. Journal of Orthopaedic and Sports Physical Therapy, 44(10), 733–738. https://doi.org/10.2519/jospt.2014.5710

63 Schache, A. G., Bennell, K. L., Blanch, P. D., & Wrigley, T. v. (1999). The coordinated movement of the lumbo-pelvic-hip complex during running: a literature review. In Gait and Posture (Vol. 10). www.elsevier.com/locate/gaitpos

64 Schache, A. G., Blanch, P. D., Rath, D. A., Wrigley, T. v, Starr, R., & Bennell, K. L. (n.d.). A comparison of overground and treadmill running for measuring the three-dimensional kinematics of the lumbo±pelvic±hip complex. www.elsevier.com/locate/clinbiomech

65 Schache, A. G., Blanch, P., Rath, D., Wrigley, T., & Bennell, K. (2002). Three-dimensional angular kinematics of the lumbar spine and pelvis during running. In Human Movement Science (Vol. 21). www.elsevier.com/locate/humov

66 Schmitz, A., Russo, K., Edwards, L., & Noehren, B. (2014). Do novice runners have weak hips and bad running form? Gait & Posture, 40(1), 82-86. doi:10.1016/j.gaitpost.2014.02.014

67 Schneiders, A. G., Davidsson, A., Hörman, E., & Sullivan, S. J. (2011). Functional movement screen normative values in a young, active population. International Journal of Sports Physical Therapy, 6(2), 75. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/21713227

68 Schreiber, C., & Becker, J. (2020). Performance on the single-legged step down and running mechanics. Journal of Athletic Training, 55(12), 1277–1284. https://doi.org/10.4085/1062-6050-533-19

69 Segers, V., Lenoir, M., Aerts, P., & De Clercq, D. (2006). Kinematics of the transition between walking and running when gradually changing speed. Gait & Posture, 26(3), 349-361. doi:10.1016/j.gaitpost.2006.10.013

70 Stamatakis, E., & Chaudhury, M. (2008). Temporal trends in adults' sports participation patterns in england between 1997 and 2006: The health survey for england. British Journal of Sports Medicine, 42(11), 901-608. doi:10.1136/bjsm.2008.048082

71 Stensrud, S., Myklebust, G., Kristianslund, E., Bahr, R., & Krosshaug, T. (2011). Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. British Journal of Sports Medicine, 45(7), 589-595. doi:10.1136/bjsm.2010.078287

72 Ugalde, V., Brockman, C., Bailowitz, Z., & Pollard, C. D. (2015). Single leg squat test and its relationship to dynamic knee valgus and injury risk screening. Pm & R, 7(3), 229-235. doi:10.1016/j.pmrj.2014.08.361

73 van der Worp, Maarten P, ten Haaf, Dominique S. M, van Cingel, R., de Wijer, A., Nijhuis-van der Sanden, Maria W. G, & Staal, J. B. (2015). Injuries in runners; A systematic review on risk factors and sex differences. PloS One, 10(2), e0114937. doi:10.1371/journal.pone.0114937

74 van Gent, R. N., Siem, D., van Middelkoop, M., van Os, A. G., Bierma-Zeinstra, S. M. A., & Koes, B. W. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. British Journal of Sports Medicine, 41(8), 469-480. doi:10.1136/bjsm.2006.033548

75 Videbæk, S., Bueno, A., Nielsen, R., & Rasmussen, S. (2015). Incidence of running-related injuries per 1000 h of running in different types of runners: A systematic review and meta-analysis. Sports Medicine, 45(7), 1017-1026. doi:10.1007/s40279-015-0333-8

76 Whatman, C., Hing, W., & Hume, P. (2011). Kinematics during lower extremity functional screening tests–Are they reliable and related to jogging? Physical Therapy in Sport, 12(1), 22-29. doi:10.1016/j.ptsp.2010.10.006

77 Willson, J. D., & Davis, I. S. (2008). Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. Clinical Biomechanics (Bristol), 23(2), 203-211. doi:10.1016/j.clinbiomech.2007.08.025

78 Willwacher, S., Sanno, M., & Brüggemann, G. P. (2020). Fatigue matters: An intense 10 km run alters frontal and transverse plane joint kinematics in competitive and recreational adult runners. Gait and Posture, 76, 277–283. https://doi.org/10.1016/j.gaitpost.2019.11.016

10 Appendices

Research project "Fatigue development in non-exhaustive running "

Questionnaire

Date:

Name's initial: Research ID:

FMS order:

Age:

Gender: ☐ Female ☐ Male ☐ Other

Weight: __________ kg Height: _________ cm BMI: __________

Leg length: Right __________ Left __________

Leg dominance/preference:

Health status:

Previous injuries:

- **Following questions are related to your running practice.**

Running experience: 3 to 6months ☐ ☐ 6 to 9 months

9-12 months ☐ ☐ Over 12 months _______________

How many days a week do you run? 1 2 3 4 5 6

Average distance per week (kilometers): ____

Number of training sessions per week: ____

What is the average 5km and 10km pace (km/min)? ____________________________________

Do you participate in any other sports activities or exercise? ____________________________

____

Previous participation in sports: ☐ ski ☐ team sports ☐ strength training
☐ Others

- If you have checked one of the items above, which sports and for how long have you practiced it?

____

____

Kiitos.