A BIOMECHANICAL ANALYSIS OF THE REALIZATION OF ACTUAL HUMAN GAIT TRANSITION

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GENT 2006

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FACULTY OF MEDICINE AND HEALTH SCIENCES
DEPARTMENT OF MOVEMENT AND SPORTS SCIENCES

A biomechanical analysis of the realization of actual human gait transition

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Gent 2006

Thesis submitted in fulfilment of
the requirements for the degree of
doctor in Physical Education

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ACKNOWLEDGEMENT

This research was supported by BOF-RUG B/03796/01-IV1.

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DANKWOORDJE - ACKNOWLEDGEMENTS

Nu het er eindelijk is, val ik stil
Er zijn zoveel mensen die ik bedanken wil

In de eerste plaats dank ik de Universiteit Gent
Die me een onderzoeksbeurs (BOF–RUG B/03796/01–IV1) heeft toegekend
En me in de vakgroep bewegings- en sportwetenschappen een bureau heeft gegeven
Al waar het zeer aangenaam was om te werken en te leven

Prof. Dr. D. De Clercq en Prof. Dr. P. Aerts waren mijn promotoren
Dirk en Peter, bedankt dat ik jullie (bijna) altijd mocht storen
Bedankt voor jullie enthousiasme, geduld, inbreng, kritiek,…
De levendige conversaties, jullie hevige repliek

Dirk, ieder detail, elk woord was doordacht en moest juist zijn
Op het moment zelf soms vervelend maar achteraf dubbel zo fijn
Bedankt! Jij gaf mij een onderzoekskans
En steeds weer die positieve stimulans

Peter, op een heel andere manier
Gaf jij me steeds weer en meer werkplezier
Eender hoeveel werk, ik kan rekenen op een snel antwoord
Je uiterste alerte geest heeft het steeds gezien of gehoord

Prof. Dr. M. Lenoir zat ook steeds klaar om me te begeleiden
En me van mijn statistiekproblemen te bevrijden
Matthieu, ook al had je dikwijls niet veel tijd
Ik mocht altijd binnen en kon mijn probleem dan kwijt
Bij elke transitievergadering was je daar
En stond je met ideeën en wetenschappelijke inbreng klaar

Furthermore I would like to thank the examination board
From our country or far overbroad

Prof. Dr. J. Whitall, Prof. Dr. P. Willems, Prof. Dr. M. Van Leemputte, Prof. Dr. B.
Van Gheluwe, Prof. Dr. W. Derave and Prof. Dr. I. De Bourdeaudhuij
Thank you for all your constructive remarks on my book
I appreciate the time and the effort it took.

Zoals een collega van me onlangs zei: met een goeie werksfeer
Doe je -verdorie- toch zoveel meer!
Anneleen, ik zal het nooit vergeten
Zelfs als ik sterf zal ik nog weten
Dat druk kracht per oppervlakte-eenheid is
Wees maar zeker dat ik me nooit meer vergis
Maar je was meer dan druk alleen…uiteraard!
Ontspanning, reizen, plezier, sport, … en heel emo van aard

Liesbeth en Isa, twee maatjes om mee te gaan lopen
Of om spulletjes in de delhaize te gaan kopen
Om mee te praten en ontspannen…
Daardoor was de boog niet altijd gespannen!

Kristof en Philippe, mijn twee gangtransitiegenoten
Kristof als jong veulen ben je snel in gang geschoten
Ik sta versteld van je enthousiasme en resultaten
Liverpool zal onze beide onderzoeken nog baten
Philippe ambitieus, zeker niet de gemakkelijkste weg
En jammer genoeg af en toe wel eens pech

Jos en Frederik, uitgeweken naar Engeland
Is het daar dan echt zo plezant?
Bedankt voor de animatie, de macro's, de sfeer
De fantastische verslagjes van ginder, keer op keer!
Pierre, Davy, Noël, jullie glimlach en helpende hand
Eenvoud in combinatie met gezond verstand
Maken de proeven haalbaar, realiseerbaar
Aangenaam, plezant en leefbaar

Anne, Daniël, Jan, Katrien, Lies, Roel, en alle andere collega's die er voor zorgen
dat je steeds weer uit kijkt naar de dag van morgen!

Proefkonijnen en koninnen, zonder jullie was ik er nooit geraakt
Uiteindelijk hebben jullie dit doctoraat, deze studie mogelijk gemaakt
Bedankt voor jullie tijd, moeite en inzet bij de testen!
Kevin en Karlien, bedankt voor de verwerking, jullie deden het als de besten!

Bovendien had ik een wereldkampioen
Om een deel van de qualisysverwerking te doen.
Een dikke merci voor bine
Is het minste wat ze heeft te verdienen

Vrienden en vriendinnen
Ik ga alvast met een welgemeend 'dank je' beginnen

De CM-vriendenkring is er één zoals geen andere
Ik hoop dat dat nooit meer zal veranderen
K@l1, zonder morren of commentaar
Maakte je mijn boek mooi. Ik vind het prachtig, echt waar!
Rom, mijn mateke, waarom?
Tja, het hoeft niet veel woorden: daarom!
Agnes, de 'sjouwelkes' blijven me altijd bij
Lieve, ik hou zo van je lieve jij!
Stef, Jeroen, Eline, Hilde, Els, Marlies, Caroline, Annelies, An,…
Jullie maakten er elk jaar opnieuw 'een feesje' van!

Mijn maatjes van het JOPO-basketteam
Met al ons jong potentieel gooien wij die bal er altijd in!
Chrisje, als coach en zwart schaap van de bende. Een extra dikke bedankt
Voor elke keer dat je me weer vol energie hebt getankt
Lieve, mede-Palm-genoot, captano in hart en ziel, die me altijd doorziet
Nooike, Oma'tje en alle andere, weet dat ik van jullie gezelschap geniet!

Barbara bedankt om als ‘JOPO-dragon’ door de tekst te gaan
Ook al heb je der misschien niks van verstaan!
Dirk bedankt voor het bier
Dat betekent voor alleman plezier!

Hans, maak van hansoft een feit & snel
Als iemand het kan, dan ben jij het wel!
Schone familie, schoon van binnen en van buiten
Eindelijk kan ik mijn dankje aan jullie ook eens uiten!

Mijn kleine zus, merci voor meer dan ik in woorden kan vertellen
Voor de talloze toffe momenten, … Zonder jou zou ik niet veel voorstellen
Jij bent mijn kleine zus en ik ben trots op jou!
Weet dat ik geen ander zusje wou…
Mama, papa, zonder jullie steun had ik dit nooit bereikt
Ik weet dat ik niet veel tijd had en dat Harelbeke ver lijkt
Maar onze deur staat steeds voor jullie open
Op een betere meter en peter hadden wij niet kunnen hopen.

Ten laatste, eefje, jolien en …? bedankt voor het geduld, de knuffel en de kus
More, most, more than most, mosterd of all, dat bedoel ik dus…
Het weten dat jullie er zijn voor mij
Vind ik ongelooflijk onwaarschijnlijk & maakt me van binnen warm en blij.

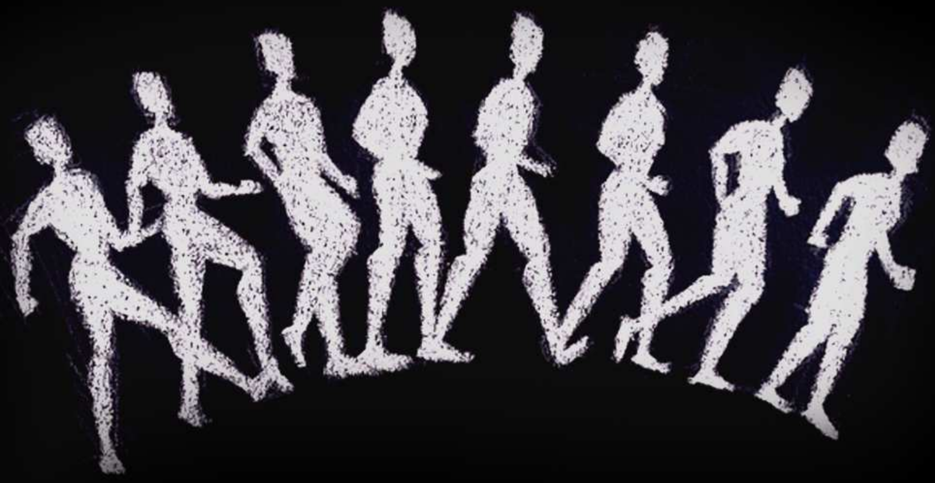
Iedereen, bedankt!

veke

PROLOGUE

Ever since mankind started to explore the world, humans have been amazed by their own body and its infinite possibilities. Since walking and running are inherent features of the human nature, it has fascinated people over the ages. The starting shot for research on locomotion was probably given by Aristotle in his study on animal locomotion "De Motu Animalium" ending with following philosophical thought: "The structure of animals, both in their other parts, and especially in those which concern progression and any movement in place, is as we have now described. It remains, after determining these questions, to investigate the problems of Life and Death." (translated by A. S. L. Farquharson, 2004). Maybe this statement was a little premature?

Only many centuries later, a first thorough study of human locomotion was conducted by Borelli (1608-1679). A few decades later, the formulation of Newton's laws introduced mathematics in (bio)mechanics (Cavagna, 1990). Thereafter, with the evolution of technology, it became possible to study aspects of locomotion invisible for the naked eye as there are high speed video camera's, infrared recording devices, ground reaction force plates, plantar pressure plates… However, to date it is still not entirely clear how the fine-tuning of the musculotendon and skeletal system is realized in locomotion, despite the vast number of studies at kinematic, kinetic and behavioural level. As such, scientists keep seeking for the answer on a simple question: How do we walk and run? How do we succeed in realizing these complex movements inherent to our bipedal human nature? With the philosophical thought of Aristotle in the back of our mind (see supra), it might be a "lifesaving" answer…



Chapter 1

Introduction

Before we focus upon the actual human gait transition, we shall give a general introduction by defining the basic forms of locomotion, namely walking and running, followed by a- brief introduction in the control of human locomotion. Those two aspects are indispensable for people not familiar with gait analysis. Experts in gait analysis and/or kinesiology can skip this first two paragraphs and continue reading at page 7, where a review on human gait transitions starts.

Walking and running

Humans have a bipedal way of moving around. Although we are capable of galloping, skipping, hopping on one or two legs, crawling on hands and feet, we primarily walk and run to move from one place to the other (Whitall and Clark, 1994). Through natural selection walking and running evolved in to economical modes of locomotion by optimizing the energy-saving mechanisms.

In the *walking* mode a pendulum-like mechanism is present where kinetic energy is exchanged for gravitational potential energy and vice versa saving up to 60-70% of the necessary mechanical energy requirements (often referred to as the inverted pendulum paradigm). Furthermore walking is used at low speeds and characterized by a more or less extended stance limb and the presence of a double stance phase (duty factor[*] > 0.5).

In *running*, kinetic and potential energy fluctuate in-phase but a substantial amount of energy is recovered through storage and return of energy in the elastic structures (the spring-mass paradigm). Besides, running is characterized by flexion of the stance limb and the presence of a flight phase (duty factor < 0.5) (Blickhan, 1989; Blickhan and Full, 1987; Cavagna et al., 1977; Mc Mahon and Cheng, 1990; Mochon and Mc Mahon, 1980; see also review Farley and Ferris, 1998).

Based on these characteristics three definitions are commonly used.

(1) The *spatio-temporal definition*: walking and running are defined by a duty factor larger, respectively smaller, than 0.5. This indicates the presence of a double stance phase respectively flight phase. (Aerts et al., 2000; Ahn et al.,

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[*] duty factor = fraction of the stride one foot contacts the ground

2004; Alexander, 1989 and 2004; Bramble and Lieberman, 2004; Donelan and Kram, 1997 and 2000; Farley and Ferris, 1998; Gatesy, 1999; Grieve and Gear, 1966; Minetti, 1998; Minetti and Alexander, 1997; Nilsson and Thorstensson, 1987; Rubenson, 2004; Segers et al., in press; Van Coppenolle and Aerts, 2004; Verstappen and Aerts, 2000; Zatsiorsky et al., 1994)

(2) The *dynamical definition* distinguishes walking from running based on the energy fluctuations of the body centre-of-mass. Walking is characterized by an out-of-phase organization of kinetic and gravitational potential energy, whereas running by an in- phase organization. (Alexander, 2003; Cavagna et al., 1977; Farley and Ferris, 1998; Mochon and McMahon, 1980; Srinivasan and Ruina, 2006; Willems et al., 1995)

(3) The *kinematic definition* looks at the configuration of the stance limb at midstance. Extension typifies walking; flexion running. (Biewener et al., 2004; Novacheck, 1998)

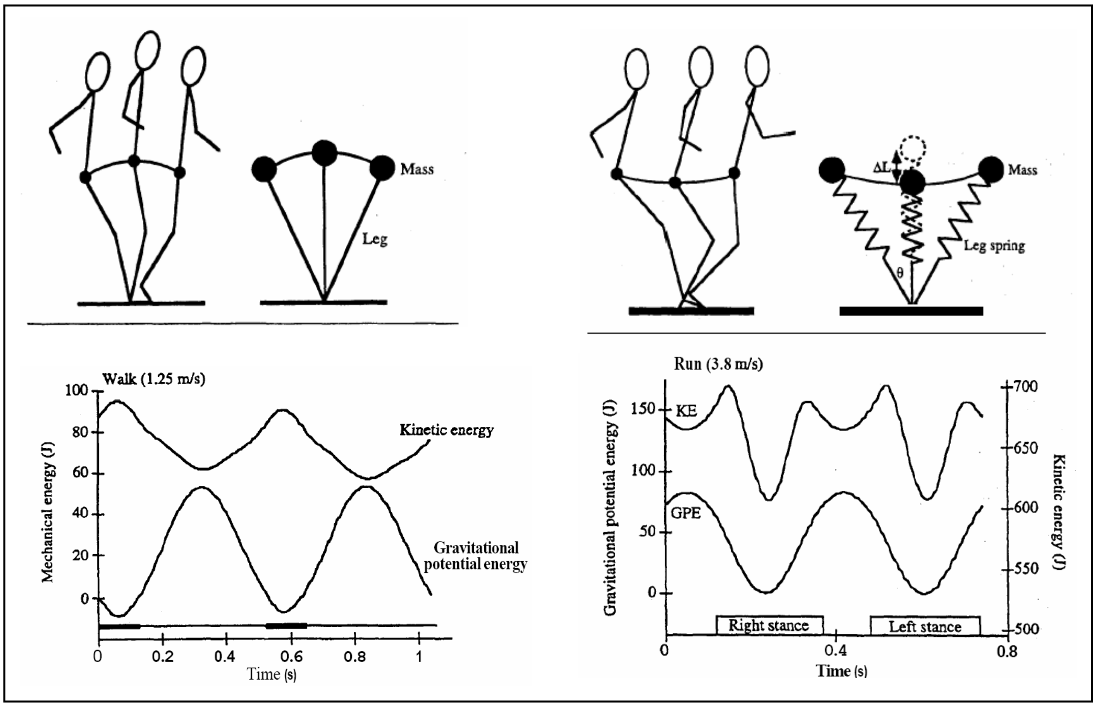

Figure 1. Schematic representation of walking and running *(Farley and Ferris, 1998)*
Inverted pendulum paradigm for walking (a) characterized by out-of-phase fluctuations of gravitational potential (GPE) and kinetic energy (KE) and the presence of double stance phase (indicated by the black bold line on the X-axis) (c). Spring mass paradigm of running (b) charaterized by in-phase fluctuations of GPE and KE and the presence of a flight phase (X-axis) (d).

Dynamical systems approach: Motor control of locomotion

As can be seen in figure 2, a simple graded intentional drive descends from the higher brain stem activating a central network on a lower level (i.e. coupled central pattern generators (CPG) for locomotion) (Aerts et al., submitted; Lacquaniti et al., 1999). This network translates the simple signal in coordinated muscle-tendon actions. Feedback can tune this coordinated movement pattern but the collective output of the system (spatio-temporal characteristics, kinematics, kinetics) emerges or self-organises from the dynamical interaction of numerous variables in the body (anthropometry, inertia, tissue properties,…) and environmental parameters (gravity, surface,…).

Using the terminology of the dynamical systems theory, the behaviour of the system can be described by two parameters: (1) the order parameter that reflects the organizational status of the system (collective output of the system) and (2) the control parameter that drives the reorganization of the system (intensity of the graded intentional drive) (Diedrich and Warren, 1995, 1998a, 1998b; Haken, 1983; Hanna et al., 2000).

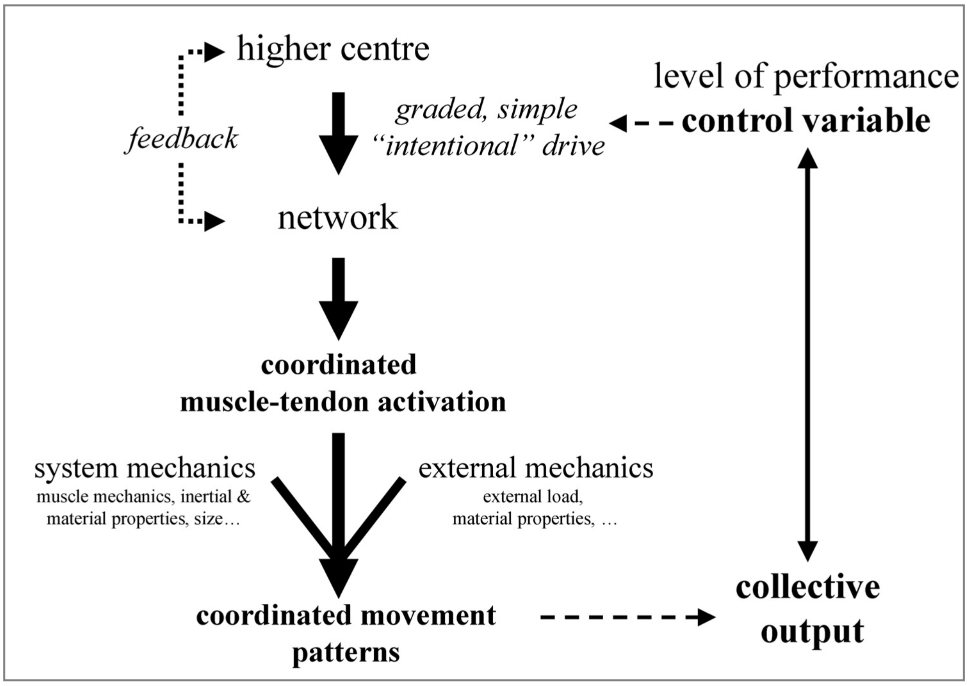

Figure 2. Simple representation of the control of human locomotion
(Personal conversation Prof. Dr. P. Aerts, also submitted to Journal of Integrative and Comparative Biology)

When continuously changing the control parameter (e.g. speed) preservation of a gait pattern is maintained over a wide range of speeds. As speed increases, the order parameter moves away from the walking attractor, a preferred configuration of the locomotor system. The coordination pattern then becomes “unstable” which is characterized by an increased variability, then suddenly jumps to the running attractor with a different but again relatively stable pattern.

HUMAN GAIT TRANSITIONS: A REVIEW.

The difference between walking and running seems very obvious, being no point of discussion (Fig. 1, p. 4, definitions p. 3-4).

However, looking for example at speed walking, dubious referee calls are a matter of course and often interfere with the opinion of athlete and spectator. Although speed walking is characterized by a specific technique, in this case walking and running do not seem to be so different.

One of the possible explanations is that unconsciously different definitions are applied. By example, it could be possible to generate a flight phase with out-of-phase fluctuations of energy (Groucho running, McMahon et al., 1987). Some birds, crabs, primates and elephant, for instance, show dynamic running, while still walking spatio-temporally (e.g. Alexander and Jayes, 1978; Blickhan and Full, 1987; Gatesy, 1999; Gatesy and Biewener, 1991; Hutchinson et al., 2003; Kimura, 1996; Muir et al., 1996; Schmitt, 1999 and 2003), also known as 'grounded running' (Rubenson, 2004) or Groucho running (McMahon et al., 1987).

Taken these thoughts into account, one might wonder what happens when humans change their gait pattern. Before formulating questions and seeking answers, one could ask why we should be interested in gait transitions at all. According to Farley and Ferris (1998) understanding the transition between walking and running may offer insight in the key factors that shape human locomotion.

Evaluation of the collective output during human gait transition (right side, Fig. 2, p. 5) might reveal aspects of the interplay between the fundamental neural and mechanical components of control (left side, Fig. 2). Such knowledge is essential to unravel the level of self-organization in motor control (Aerts et al., 2000, submitted; Diedrich and Warren, 1995), or to assess the compliant control of robots (Alexander, 2005; Sellers et al., 2005; Seyfarth, 2005).

By discovering general principles of locomotor control, we could apply them to improve human health (Ferris et al., 2005; Perry, 1992). For example, this knowledge is useful in manufacturing robotic exo-skeletons, improving gait rehabilitation after spinal cord injury or stroke (Ferris et al., 2005).

Therefore, the main purpose of this review is to give a detailed literature overview of the available answers on the three following questions: (1) At which speed people spontaneously prefer running above walking and vice versa when increasing respectively decreasing speed? (2) Does this natural transition appear as a clear discontinuity or as a smooth change? (3) Why do humans switch from one gait to the other? Furthermore we shall seek out consistencies and different opinions in the existing transition-literature.

QUESTION 1:

AT WHICH SPEED PEOPLE SPONTANEOUSLY PREFER RUNNING ABOVE WALKING AND VICE VERSA WHEN INCREASING RESPECTIVELY DECREASING SPEED?

When a person is moving with altering speed, stride length and stride frequency are adapted to result in an optimal combination (Mercier et al., 1992). The increase or decrease in speed beyond a certain speed will generally involve a walk-to-run transition (WRT), respectively run-to-walk-transition (RWT) that occurs spontaneously at a speed of approximately 2 m s^{-1} (Table 1) although people can walk at higher speeds and run at lower speeds.

A part of the variation in reported transition speed can be explained by the use of different protocols used to manipulate locomotion speed. In the next section we shall discuss these methodological issues one has to keep in mind.

1. Ramped protocol versus Stepped protocol

In transition research, two types of protocol are used to manipulate speed: (1) a stepped protocol in which the manipulation of speed occurs in discrete steps and (2) a constantly accelerating protocol or ramped protocol.

Most researchers applied a stepped protocol. Each subject walked and ran at different speeds during a specific time interval (mostly 30 sec), leaving the subjects a decision time. The first speed at which subjects actually chose to run when speed increased is called the WRT. In a protocol with decreasing speed the first speed at which subjects preferred walking over running is called the RWT. Obviously, the actual transition step cannot be studied.

The ramped protocol is not used as often as it demands an accurate tuning of the treadmill and is not so practical because of the constant acceleration/deceleration. However, it offers the researcher the possibility to study the actual transition from one gait to the other, the nature of human gait transitions (sudden versus gradual process) and the discrepancy between WRT and RWT (hysteresis: see point 3, below, p. 11).

Comparing both protocols, similar gait transition speeds (averaged over all researches) were found. WRT-speed is 2.06 respectively 2.06 m s^{-1} and RWT-speed is 2.03 respectively 2.01 m s^{-1} for the ramped and stepped protocol. Although apparently these transition speeds do not differ, the results of these two types of protocol might refer to two different phenomena. In the ramped protocol, it concerns the actual transitions across the transition point, whereas in the stepped protocol it is more a conscious decision.

Another difference between both protocols is that the accuracy of the reported transition speed is different in both protocols. For example, increasing the treadmill every step with 0.1 m s^{-1} delivers an accuracy of 0.1 m s^{-1} whereas in the ramped protocol it is only limited by the recording frequency (240 Hz in present study) resulting in an average accuracy of 0.01 m s^{-1}.

2. Treadmill versus Overground

A common discussion is the use of a treadmill in locomotion research. By studying human gait on a treadmill belt the natural environment of walking, running and by consequence the transition between both is changed. Visual flow is no longer available and concerning kinematics, energy requirements, spatiotemporal parameters and kinetics unequivocal results have been reported (Alton et al., 1998; Murray et al., 1985; Nelson et al., 1972; Nigg et al., 1995; Pierrynowski et al., 1980; Savelberg et al., 1998; Stolze et al., 1997; Wank et al., 1998; White et al., 1998). However, for studying locomotion it offers benefits such as less space requirements, ease of assessing the subject, EMG-research, …

According to our knowledge, besides the abstract of Johnson and Li in 2000, no study has examined gait transition overground. Johnson and Li indicated differences between transition speed overground and on a treadmill.

We did a small experiment with four subjects to compare transition speed overground and on a treadmill (Malcolm et al., 2005). First WRT and RWT on the treadmill were determined using a ramped protocol with accelerations of 0.05, 0.07 and 0.1 m s^{-2} respectively deceleration of -0.05, -0.07, -0.1 m s^{-2}. Afterwards, subjects followed a constantly accelerating light (with according accelerations - decelerations) on a walkway. We found that only the WRT-speed was affected and systematically lower on a treadmill, due to the altered psychological, environmental and other constraints. Despite the small population used, it indicates that environmental constraints influence the transition phenomenon.

3. WRT versus RWT, or Hysteresis?

The direction of speed change (accelerating or decelerating) might influence transition speed and cause a difference between the WRT- and RWT-speed. Although it is common to study the WRT-speed, starting from a low speed and gradually increasing speed (in steps or constantly), the RWT is equally important, because WRT and RWT could phenomenologically be different.

The discrepancy between WRT and RWT-speed is also called hysteresis. As can be seen in Table 1, hysteresis is not always present. Even when a significant effect is found, actual differences between WRT- and RWT-speed are small. In a stepped protocol a hysteresis effect was found by Abernethy et al. (1995, Δ[*] = 0.11), Getchell and Whitall (2004, Δ = - 0.12), Hanna et al. (1996, 2000, Δ = 0.10) and Turvey et al. (1999, Δ = -0.08).

To explore hysteresis a ramped protocol is a more appropriate method rather than the more artificial stepped protocol because speed is continuously changing (Hanna et al., 2000). In a ramped protocol this was observed by Diederich and Warren (1998b, Δ = 0.11), by Thorstensson and Roberthson (1987, Δ = 0.07) and by Li (2000) who concluded that acceleration magnitude influences hysteresis: lower accelerations led to RWT > WRT and higher accelerations to WRT > RWT.

Despite the ambiguous findings on the hysteresis between WRT- and RWT-speed, it is not inconceivable that WRT and RWT are determined by other factors although this results -by coincidence- in the same transition speed. Therefore, the author is not an advocate of using the preferred transition speed (PTS) as the mean of WRT and RWT.

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[*] Δ is calculated by extracting RWT-speed from WRT-speed (expressed in m s-1). Positive values mean that WRT> RWT and negative values indicate that RWT>WRT.

Author(s)	Year	Subjects	Ramped protocol	Acceleration (ms^{-2})	WRT	RWT	PTS	Treadmill
			Stepped Protocol	'Step size' ($m\ s^{-1}$)	Speed ($m\ s^{-1}$)			Overground
			Constant velocities	-				
Abernethy et al.	1995	15	Stepped Protocol	0.08	2.16	2.05	2.11	Treadmill
		4	Ramped Protocol	Not reported	2.00	1.89	1.95	Treadmill
Abernethy et al.	2002	11	Stepped protocol	0.08	2.09			Treadmill
Beaupied et al.	2003	15	Constant Velocities	-				Treadmill
Daniels and Newell	2003	12	Stepped Protocol	0.1	2.05			Treadmill
Diedrich and Warren	1995	8	Constant Velocities	-				Treadmill
		8	Ramped protocol	Not reported	2.19	2.15	2.17	Treadmill
Diedrich and Warren	1998a	8	Constant Velocities	-				Treadmill
Diedrich and Warren	1998b	8	Ramped protocol	Not reported	2.17	2.06	2.12	Treadmill
		8	Stepped Protocol	0.083	2.12	2.12	2.12	Treadmill
Farley and Ferris	1998	review	Walking- Running					
Fewster and Smith	1996	10	Stepped Protocol	0.2			2.07	Treadmill
Getchell and Whitall	2004	24	Stepped Protocol	0.055	1.77	1.89	1.83	Treadmill
Hanna et al.	1996	17-25	Stepped Protocol	0.08			2.16	Treadmill
Hanna et al.	2000	45	Stepped Protocol	0.08	2.21	2.11	2.16	Treadmill
Hreljac	1993a	20	Stepped Protocol	0.1-0.2	2.09	2.00	2.05	Treadmill
Hreljac	1993b	20	Stepped Protocol	0.1-0.2			2.05	Treadmill
Hreljac	1995a	20	Stepped Protocol	0.1-0.2			2.06	Treadmill
Hreljac	1995b	28	Stepped Protocol	0.1-0.2			2.05	Treadmill
Hreljac and Ferber	2000	25	Stepped Protocol	Not reported			1.99	Treadmill
Hreljac et al.	2002	12	Stepped Protocol	0.1-0.2			1.99	Treadmill
Hreljac et al.	2001	9	Stepped Protocol	0.1-0.2			1.94	Treadmill
Johnson and Li	2000	14		-				Overground Treadmill
Kao et al.	2003	10	Stepped Protocol	0.05				Treadmill
Kram et al.	1997	9	Stepped Protocol	0.1	1.98			Treadmill
Li	2000	20	Stepped Protocol	?	2.25	1.84	2.05	Treadmill
		20	Ramped protocol	0.04,0.06,0.08,0.1,0.12	2.25	2.30	2.28	Treadmill
Li and Hamill	2002	20	Ramped Protocol	0.04,0.06,0.08,0.1,0.13	1.90	1.85	1.88	Treadmill

Li et al.	1999	6	Constant Velocities	-	2.24			Treadmill
Malcolm et al.	2005	4	Ramped Protocol	0.05, 0.07, 0.1				Overground Treadmill
Mercier et al.	1994	7	Stepped Protocol	0.14	2.16			Treadmill
Minetti et al.	1994	5	Stepped Protocol	0.03	2.12			Treadmill
Mohler et al.	2004	24	Ramped Protocol	0.1	2.11	1.86	1.98	
Neptune and Sasaki	2005	10	Stepped Protocol	0.1	1.96			Treadmill
Nilsson and Thorstensson	1986	8	Constant Velocities	-				Treadmill
Nilsson and Thorstensson	1989	12	Constant Velocities	-				Treadmill
Nilsson et al.	1985	10	Constant Velocities	-				Treadmill
Prilutsky and Gregor	2001	7	Stepped Protocol	0.1-0.2	2.10	2.10	2.10	Treadmill
Raynor et al.	2002	18	Stepped Protocol	0.11	1.99	2.00	2.00	Treadmill
Rotstein et al.	2005	19	Stepped Protocol	0.05			2.03	Treadmill
Sasaki and Neptune	IP	10	Stepped Protocol	0.1	1.96			Treadmill
Sasaki and Neptune	2006	10	Stepped Protocol	0.1	1.96			Treadmill
Seay et al.	2006	11	Stepped protocol	0.1				Treadmill
Thorstensson and Roberthson	1987	18	Ramped Protocol	0.05,0.08,0.11	1.92	1.85	1.89	Treadmill
Tseh et al.	2002	3*10 (children)	Stepped Protocol	0.045	2.06			Treadmill
Turvey et al.	1999	11	Ramped Protool	Not reported	2.02	2.10	2.06	Treadmill
Usherwood and Bertram	2003	6	Constant velocities	-				Treadmill
Mean		Adults	Ramped Protocol		2.06	2.03	2.05	
Standarddeviation			Ramped Protocol		0.15	0.19	0.17	
Mean		Adults	Stepped Protocol		2.06	2.01	2.04	
Standarddeviation			Stepped Protocol		0.12	0.10	0.08	

Table1. Summary existing literature.

Acceleration indicates the acceleration of the treadmill when gradually changing speed across transition speed. Step size is the speed differences between successive steps in the stepwise protocol. Ramped protocols are indicated with light grey (spiked) boxes, when PTS was not reported but could be calculated as the mean of WRT and RWT-speed, the box is coloured grey.

4. Subjects or modelling

Most researches in human locomotion use subjects to explore movement patterns, muscular activity or kinetic parameters. A lot of data collection can be avoided, if motion is replicated using musculoskeletal models. Only recently, this technique is applied by Neptune and Sasaki to simulate gait transitions. Generally it concerns a valid representation of the movement but one should bear in mind that small errors are intrinsic to modelling, although advanced optimization techniques are used to minimize these errors (Caldwell, 2004; Neptune and Sasaki, 2005). For example, the modelling of muscles using the Hill type muscle do not account for all relationships between force, length, velocity and activation (Caldwell, 2004; Huijing, 1998).

Question 1: At which speed people spontaneously prefer running above walking and vice versa when increasing respectively decreasing speed?

At a speed of approximately **2 m s^{-1}** (7.2 km h^{-1}) humans prefer to switch from one gait to another regardless the **protocol** used (ramped/stepped) and the **direction of speed change** (WRT/RWT). The use of a **treadmill** offers benefits in locomotion research but also influences both locomotion patterns and the transition speed. Musculoskeletal **modelling** might offer benefits although small errors are inherent to such an approach.

QUESTION 2:

DOES THIS NATURAL TRANSITION APPEAR AS A CLEAR DISCONTINUITY OR AS A SMOOTH CHANGE?

This question can be rephrased to: Does transition occur as a break point in the locomotion pattern or as a process gradually evolving from one mode to the other (see Fig. 1).

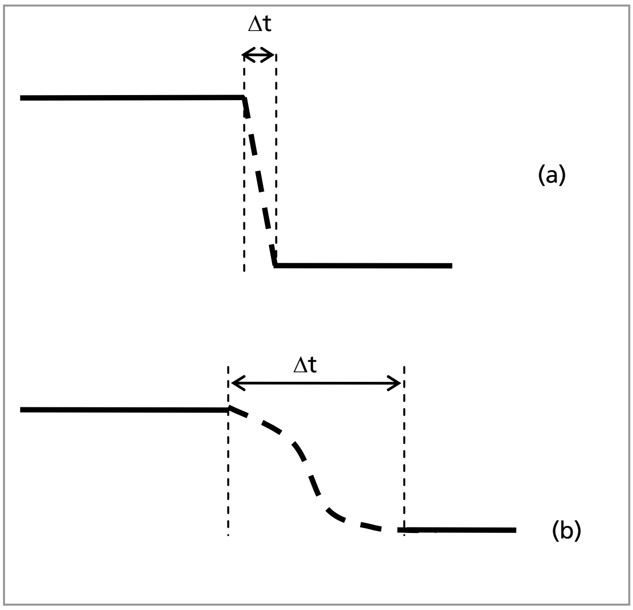

Figure 3. Transition, an event or a process?
Full black lines represent a stable gait pattern. The dashed line represents the transition between both with transition as a
(a) a sudden jump or event
(b) process gradually evolving from one gait to the other

As mentioned before (Question1, a), to identify the nature of transition (process versus event) a ramped protocol should be applied. Otherwise, the spontaneous character of transition disappears and the preparation of transition is lost in the stepwise increase/decrease of speed.

Most researchers take the transition as an event for granted. Looking at the spatiotemporal definitions it is as plain as a pikestaff that humans are either walking either running: a double stance phase is present or not and transition consequently occurs in one step.

To the contrary, indications for gradually changing gait characteristics are present, even in the stepped protocol: for example an increase in variability is observed in the approach to transition (Diedrich and Warren, 1995). Therefore, it could be that the steps leading to, and following transition exhibit a unique behaviour to prepare or to complete the transition.

There are only few studies that applied a ramped protocol.
Thorstensson and Robertson (1987) were the first to impose a constant acceleration on the subjects. However, they only studied the influence of leg length and acceleration on the transition speed.
Li and Hamill (2002) took a closer look at the vertical ground reaction forces in the steps leading to transition and found unique characteristics for the steps before transition (Fig. 4). In the WRT they found an increase in the first peak force, a decrease of the depression between the two peak forces and a decrease of the second peak force in the last walking step before transition. The first peak forces and the depression between the maxima were found to interact with the imposed acceleration. The normal symmetry in the double hump ground reaction pattern is no longer present approaching the WRT (Fig. 4a). In the RWT the impulse increased linearly in the five last running steps approaching transition. Peak force decreased especially in the last running step and the time to peak force decreased dramatically during the last two steps prior to transition (Fig. 4b). This transitional behaviour possibly indicates adaptation to prepare the locomotor system for transition.

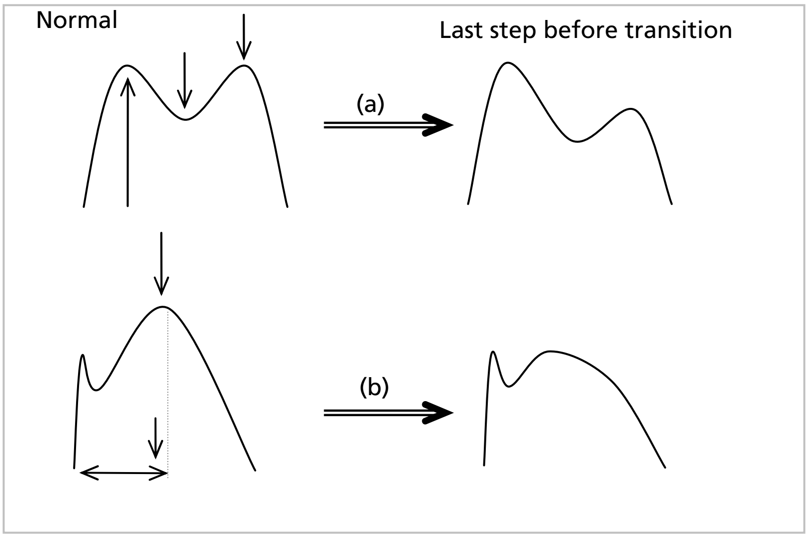

Figure 4. Changes in vertical ground reaction forces *(Li and Hamill, 2002)*

(a) In the walking steps before WRT: increase first peak, decrease through and decrease second peak
(b) In the running steps before RWT: decrease peak force and decrease time to peak force.

Li and Hamill do not report what actually happens at transition. Is there a sudden change from a double hump to a one hump pattern in the WRT and vice versa in the RWT? We only wanted to emphasize that transition is probably merely realized during one step or stride but that a process covering several steps, with adaptations to prepare the system for transition (preparation) or to complete transition (post-paration), could also be present.

It is clear that this matter still needs a lot of research!

Question 2: Does this natural transition appear as a clear discontinuity or as a smooth change?

As a general conclusion WRT and RWT appear as events and are **mainly realized in one stride**. Nevertheless a process could be present during which the transition is completed to continue locomotion in a stable new gait pattern.

QUESTION 3:

WHY DO HUMANS SWITCH FROM ONE GAIT TO THE OTHER?

This question, related to the quest for processes or mechanisms underlying fundamental changes in coordination (e.g. gait transitions), intrigued motor behaviour researchers and biomechanists for some time. An obvious and logical explanation for switching to another gait pattern is that humans are no longer capable of continuing in the present gait. But, as mentioned before, humans spontaneously make the switch despite the fact that they can walk at speeds higher than the WRT-speed and run at speeds lower than the RWT-speed. Before we browse through literature for possible explanations, some of the basic assumptions and theories will be explained.

Researchers went looking for trigger(s) for gait transition. Hreljac (1993) formulated four criteria in order to label a variable as trigger. The variable had to (1) change abruptly to a (2) different value at a (3) critical point that had to remain (4) constant in different conditions (Fig. 5). In the available literature, numerous triggers (mechanical, energetic, …) have been proposed.

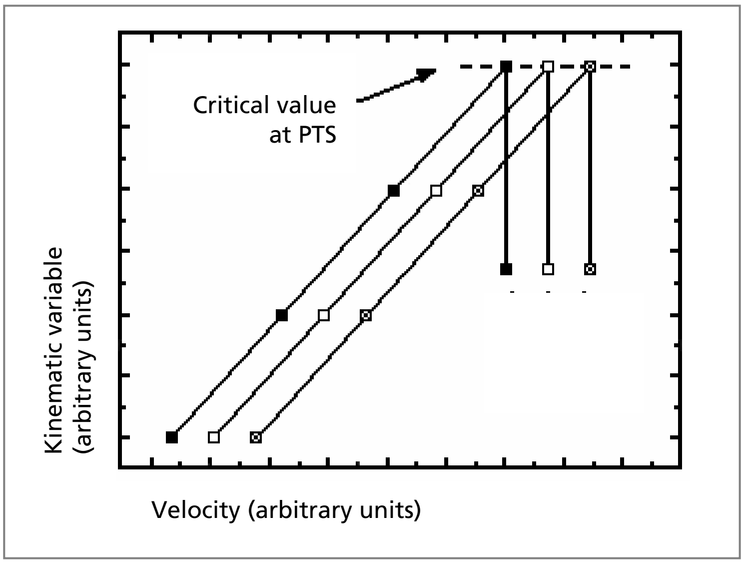

Figure 5. Trigger *(Hreljac, 1993)*
Before transition there is an increase of the variable in different conditions (☒, ☐ and ■). For example the incline of a treadmill) until a critical value is reached (same in all conditions), then suddenly drops to a lower value after transition.

One of the reasons for this inconsistency (theory of one trigger versus many determinants found in literature) could be that WRT and RWT are not triggered by one factor but by a pool of determinants. In this type of theory gait transitions are the result of multifaceted interaction of psychophysiological stimuli (Daniels and Newell, 2003). Transition speed is then logically determined by the weakest link in the chain. Strengthening this determinant, however, does not necessarily lead to higher transition speeds (Fig. 6). Let's illustrate this by a simple physiological example. Maximal performance in cycling is related to maximal oxygen uptake. Hypoxia (lowering the oxygen percentage in the air) diminishes maximal performance, but hyperoxia (higher oxygen percentage) does not improve performance. Examining gait transition's determinants and the hierarchical order between them could lead to insights in the *complexity of this simple task* for humans. We might thus unravel this '*contradictio in terminis*' (complex organization of the human locomotor system versus the ease of execution).

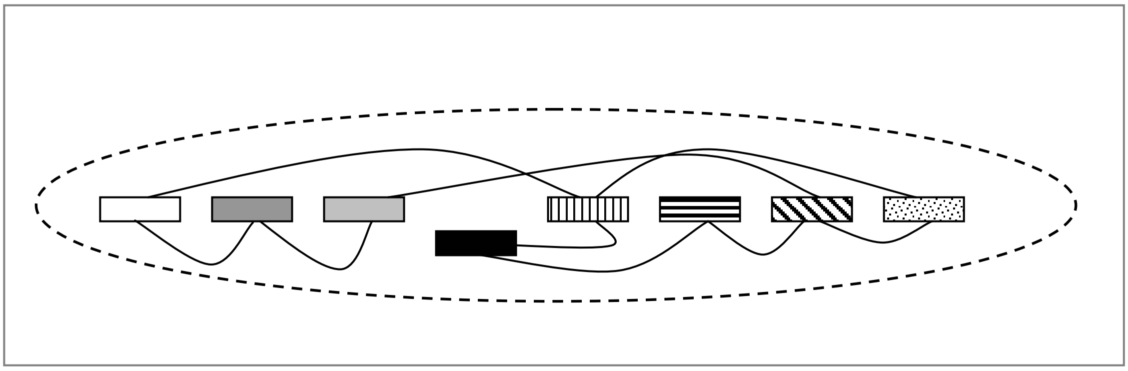

Figure 6. A pool of determinants

Complex interactions can be observed between the determinants. In this configuration the black determinant is the weakest link in the chain. However, strengthening this black determinant does not necessarily lead to higher transitions speeds as this might affect the relationship with other factors.

Some researchers apply the dynamical systems theory that views behaviour as a consequence of the dynamics of the action system within task constraints (e.g. Diedrich and Warren, 1998b; Kelso, 1995; Kugler and Turvey, 1987, see also Fig. 2, p. 5). Stable posture and movement patterns are determined by the interaction of nonlinear components within the human system (Hanna et al., 2000, see also p. 5). According to the dynamical systems theory, transition emerges when the control parameter reaches a critical value and the system changes from one stable attractor (i.e. walking in WRT, running in RWT) to another stable attractor (i.e. running in WRT, walking in RWT).

In this paragraph we shall comment on the possible determinants of human gait transition, as described in literature. A subdivision is made by adjudging them to one of the following categories: energetic, mechanical, muscular and kinematic, cognitive or dynamical.

1. Energetic optimization?

Alexander (1989) argued that minimization of energy cost is predominantly important in determining terrestrial gaits. In particular this has been shown for ponies in a wide range of speeds (Fig. 7: Bramble and Lieberman, 2004; Hoyt and Taylor, 1981).

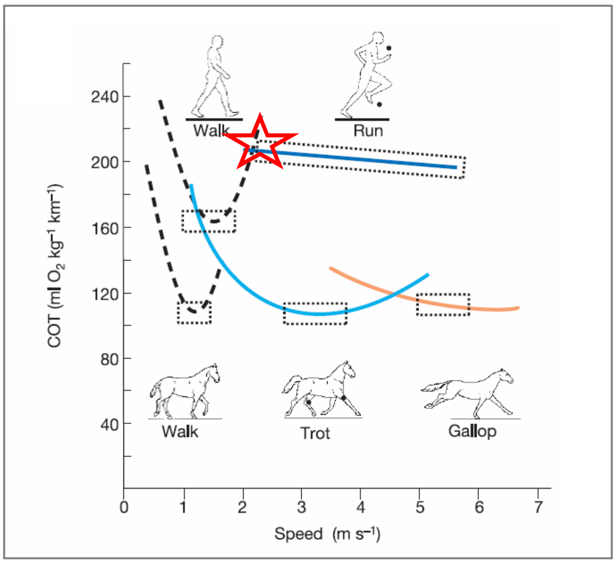

Figure 7. Energy cost in humans and quadrupeds
(Bramble and Lieberman, 2004)
Comparison of the metabolic cost of transport (COT) in humans and ponies. Both species have U-shaped COT curves for walking, and trotting has a similar-shaped curve in the horse. The human COT is essentially flat during running.
The red star indicates the energetically optimal transition speed (EOTS), at the intersection of walking and running metabolic energy curves.

In human locomotion kinematic and kinetic organization is optimized to minimize energy expenditure at preferred walking and running speed (Bramble and Lieberman, 2004; Margaria, 1963). Therefore, it seems logical that the transition between these two intrinsic gait patterns is driven by energetic constraints (Hanna et al., 2000; Raynor et al., 2002). However, the concordance of the energetic optimal transition speed (EOTS = speed at the intersection of walking and running metabolic energy curves, Hreljac, 1993a, red star in Fig. 7) and the PTS is disputed by Beuter and Lefebvre (1988), Hreljac (1993a), Minetti (1994), Raynor et al. (2002), Rotstein et al. (2005) and Tseh et al. (2002).

Energy cost does not appear as an appropriate signal to be sensed for gait change as it seems unlikely that humans would directly perceive energetic cost and act upon it on a step-to-step basis (Farley and Taylor, 1991; Hreljac, 1993a; Hreljac et al., 2001; Saibene and Minetti, 2003). According to Minetti (1994) and Saibene and Minetti (2003), this could be explained by the fact that transition speed is an artificial concept since humans jump to a higher speed at WRT during a spontaneous overground acceleration.

Energy optimization is supposed to be linked to effort. However, if peripheral receptors are dealing with an uncomfortable situation (by example: muscle overexertion), they could provide a signal to switch to another gait pattern despite the increase in energetic costs. Locomotion comfort (local factor) is then chosen above metabolic savings (central factor). This can be related to the rate of perceived exertion (RPE) that is higher when walking at transition speed compared to running at transition speed (Hreljac, 1993 and 2001; Rotstein, 2005). Central RPE increased across transition speed (Daniels and Newell, 2003; Prilutsky and Gregor, 2001; Rotstein, 2005) but peripheral demands (local factor of RPE) remained constant throughout transitions (Daniels and Newell, 2003). WRT is associated more with perception of exertion originating in the leg (see later, muscular factors p. 22-24) than with sensations of cardiorespiratory effort (Daniels and Newell, 2003; Prilutsky and Gregor, 2001).

Thorstensson and Roberthson (1987) claimed that transition is the result of a subjective feeling that a transition will lead to a more comfortable situation. This might be based on previous experience of the subjects in combination with information from peripheral receptors and the activity in the neural networks controlling locomotion. Maybe previous experience learned us that realizing the actual transition costs much more energy when it is postponed to higher speeds in the WRT and to lower speeds in the RWT. Usherwood and Bertram (2003) calculated that the transition step in se would be 1.75 times as expensive as an average walking or running steps at comparable speed. Despite the increase in cost of the transition step it is unlikely that this would have any effect on the gait selection.

Is it energetic optimization?

A widespread hypothesis is that animals including humans switch to another gait pattern because of 'economical' reasons. Humans, however, realize gait transition below the energetic optimal transition speed, indicating that metabolic cost is not the ultimate driving mechanism. Furthermore, it seems unlikely that humans directly perceive energetic cost. Nevertheless it remains surprising that transition occurs (2.09 m s^{-1}) in proximity of the transition speed predicted by energy efficiency (2.36 m s^{-1}).

2. Muscular or kinematic triggering?

Subjects might use information from peripheral receptors as well as from previous experience, to trigger transition and achieve a more comfortable mode of locomotion (Thorstensson and Robertson, 1987). Peripheral receptors of the lower limbs respond to acute signals from the muscles in the lower limb experiencing overexertion or ineffective working conditions (McCloskey et al., 1983; Neptune and Sasaki, 2005) and to a number of kinematic variables such as joint angular velocities and accelerations (Loeb and Levine, 1990).

2.1 Muscular factors

RPE is higher during walking at transition speed compared to running at transition speed (Hreljac, 1993 and 2001; Rotstein, 2005). The sense of perceived effort during low-intensity exercise (estimated by RPE) is thought to originate from motor outflow commands to muscles (quantified by muscle activation) and, to a lesser degree, from the afferent information about the actual force developed by the muscles (McCloskey et al., 1983).

Thus one can expect that the activation level of the leg muscles behaves similarly to the RPE. Transition is associated with more perception of exertion originating in the leg than with sensations of cardiorespiratory effort. Therefore, the activation level of the leg muscles might explain the transitions (Prilutsky and Gregor, 2001).

Author(s)	TSp* (m s^{-1})	Muscle(s)	Explanation
Hreljac et al. (2001)	PTS: 1.94	Dorsiflexor: - m. Tibialis Anterior	Overexertion → muscular stress
Prilutsky and Gregor (2001)	PTS: 2.10	WRT: Swing-related activation - m. Tibialis Anterior - m. Rectus Femoris - Hamstrings RWT: Stance related activation - m. Soleus - m. Gastrocnemius - m. Vastii	Sense of effort Due to exaggerated activation of the muscles
Neptune and Sasaki (2005)	WRT: 1.96	Plantar flexors: - m. Gastrocnemius - m. Soleus	Impairment muscle force production

Table 2. Possible muscular determinants in human gait transitions
* TSp= transition speed

Hreljac et al. (2001) examined the hypothesis of an alleviation of muscular stress on the ankle dorsiflexors when changing to the running gait in the WRT. The mean activity was found to increase with increasing speed. Peak normalized[1] EMG activity was found to increase with increasing walking speed for all muscles. This increase continued after transition, except for the TA (m. tibialis anterior) where a significant decrease was found in peak EMG situated near heel contact. Hreljac suggested that proprioceptive information is used to indicate local discomfort and fatigue in the dorsiflexors.

Prilustsky and Gregor (2001) linked the increased activation of TA, BF (m. biceps femoris) and RF (m. rectus femoris) during the swing phase of fast walking required to meet the increased joint moments during swing to the WRT. The RWT would be determined by the higher activation of the support-related muscles (Table 2) during stance of slow running, likely required for the larger displacement of the centre-of-mass during running.

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[1] Normalized to mean value when walking at preferred transition speed

Neptune and Sasaki (2005) simulated walking and running using a bipedal musculoskeletal model and found impairment of plantar flexor force production near PTS due to poor contractile conditions. The transition from walking to running would place the plantar flexors at a better operating point on the force-length-velocity relationship. This adverse contractile status can be conveyed through the integration of sensory information from the muscle spindles and Golgi tendon organs to indicate that a gait transition is necessary.

2.2 Kinematic factors

Given the consistent kinematic pattern of human locomotion (Vaughan, 2003; Winter, 1984) and capacity of proprioceptive receptors (joint receptors, muscle spindles, Ruffini endings, Golgi tendon organs: Bosco and Poppele, 2001; Dover and Powels, 2003) to act directly upon kinematic variables, it could be that transition is determined by reaching a critical value, thus triggering gait transition (Fig. 5) (Hreljac, 1995a).

Kinematics of transition are rarely examined. Hreljac (1995a) reasoned that four criteria have to be met (see above, p. 18) to label a variable as a possible trigger. After studying four kinematic variables (maximum hip extension, support length, peak ankle angular velocity and peak ankle angular acceleration) in different graded conditions (different inclinations of the treadmill: 0%, 5%, 10%), only the last two comply with all four stringent criteria. Critical values of ankle angular velocity and acceleration are reached at the transition speed near toe-off (concentric). This was confirmed by Sasaki and Neptune (in press) and Prilutsky and Gregor (2001).

Is it a muscular or kinematic trigger?

The local muscular factor could be a determinant of gait transition and switching to another gait pattern might lead to a more comfortable situation for the leg muscles decreasing the local factor of RPE. Concerning kinematics, only critical values of ankle angular velocity and acceleration are reached.

3. Mechanical limit?

As mentioned in the introduction, the simplest model of walking is an inverted pendulum in which the centre-of-mass (COM) vaults over a rigid leg. By a pendulum-like exchange of gravitational and kinetic energy up to 60-70% of the energy can be recovered. This energy exchange diminishes at higher walking speeds because muscles must provide extra mechanical energy. Cavagna (1977) hypothesized that the WRT would occur because the inverted pendulum becomes ineffective in conserving mechanical energy when compared to the elastic storage of energy used in the running gait.

The most important force that determines the inverted pendulum is gravity (= mg, where m is body mass and g the gravitational constant), which must be at least equal to the centripetal force (= mv^2/L, where L leg length and v the horizontal velocity). The ratio between both forces is called the Froude-number (= v^2/gL) (Alexander, 1989; Minetti, 2001a). A Froude-number of 1.0 determines maximal walking speed because at higher Froude-numbers feet would loose contact with the ground (Kram et al., 1997; Vaughan, 2005). In reality however, humans and other bipedal animals prefer to change from walking to running at a Froude-number of 0.5 (Alexander, 1989; Gatesy and Biewener, 1991; Hreljac, 1995b; Kram, 1997; Minetti, 2001a, 2001b; Thorstensson and Robertson, 1987; Vaughan, 2005). It remains, however, unclear why this specific Froude-number is adopted since it is not even close to the theoretically maximal walking speed (Froude-number = 1.0: Kram, 1997; Minetti, 2001).

If transition indeed consequently occurs at a Froude-number of approximately 0.5, transition speed could theoretically be altered by changing one of the factors that determine the Froude-number: gravitational constant (g) and leg length (L). This paragraph will describe the effect of reduced gravity (changing g) and differences in anthropometry (changing L) on transition speed.

3.1 Reduced gravity

In reduced gravity conditions humans make the WRT at lower absolute speeds but at comparable dimensionless speeds (i.e. Froude-number of approximately 0.5; Kram, 1997; Minetti, 2001a, 2001b). At lowest simulated reduced gravity levels, there is discrepancy between the predicted data and the actual data. This can be explained by the effect of ‘Earthly’ gravitational forces on the swinging leg (Kram, 1997; Minetti, 2001a and 2001b). Hypergravity and locomotion has only been examined by Cavagna et al. (2000) with focus on walking. They found a greater range of speeds at higher gravity (1.5 times gravity on Earth), as predicted by the Froude-number and which could give an indication towards higher transition speeds.

The transition at a constant Froude-number (± 0.5) in different gravitational conditions is consistent with a trigger induced by the mechanisms of the inverted pendulum (Kram, 1997).

3.2 Anthropometrical variables

Getchell and Whitall (1997, 2004), Hanna et al. (1997, 2000), Hreljac (1995b) and Thorstensson and Roberthson (1987) examined anthropometrical variables and correlations with transition speed (Table 3). All studies showed only weak or moderate correlations with transition speed. Overall, there was a weak tendency towards an increase in PTS with increasing leg length (Hanna et al., 2000; Hreljac, 1995b; Raynor et al., 2002; Thorstensson and Robertson, 1987).

Hanna et al. (2000) and Raynor et al. (2002) suggested that the absence of high correlations could be due to the relative anthropometric homogeneity of humans in comparison to the heterogeneity of the animal kingdom. In addition, it could be that, within the wide variety of possible anthropometrical values, the key parameter is not taken in consideration. For example: only lower leg variables were taken into account, but nothing is known about arm length or trunk characteristics. Another postulation is that the influence of anthropometrical characteristics can easily be overridden by other factors determining transition (Fig. 6).

Author(s)	TSp* (m s^{-1})	Factor highest correlation	Correlation coefficient
Thorstensson and Robertson (1987)	WRT: 1.92 RWT: 1.85	Leg length	0.3
Hreljac (1995a)	PTS: 2.05	Thigh Length	0.60
		Leg length	0.58
		Lateral Malleolus Height	0.54
		Thigh length/Sitting Height	0.58
Getchell and Whitall (2004)	WRT: 1.77	WRT:	
		Thigh Length	0.13
		Ankle Dorsiflexion	0.11
		Height	0.12
	RWT: 1.89	RWT:	
		Thigh length	0.16
		Maximal power output	0.16
Hanna, Abernethy, Neal, Burgess-Limerick (2000)	PTS: 2.16	Standing height	0.20
		Females:	
		Height	0.27
		Males:	
		Shank Length	0.35
		Leg length	0.26
Raynor, Yi, Abernethy and Jong (2002)	WRT: 1.99	WRT:	
		Standing height	0.30
		Shank Length	0.35
		Leg length	0.31
	RWT: 2.00	RWT:	
		Standing height	0.29
		Shank Length	0.35
		Leg length	0.29

Table 3. Antropometrical variables correlating with transition speed ($p<0.05$ in all studies)

* TSp= transition speed

3.3 Other mechanical limits

Minetti (1994) found a significant decrease in inter-thigh angle and asserted that the WRT occurs when this structural limit is reached. The maximal spread between limbs would be experienced as difficult, a result of stress in the ligaments and bi-articular extensor muscles at their maximum length. Some researchers question this trigger as different maxima were found at different gradients and because of this variable only accounts for the WRT and not for the RWT because a RWT is accompanied by an evolution towards a larger inter-thigh angle (Kram et al., 1997).

Is there a mechanical limit?

Because transition occurs at an approximately constant Froude-number (± 0.5) in different gravitational conditions, it seems not unlikely that some aspects of the inverted pendulum determine transition speed. Anthropometric characteristics do not convincingly correlate with transition speed probably because of the small variability in human anthropometry.

4. Kinetic stress?

In animals there is evidence that gait transitions occur to decrease mechanical stress (peak ground reaction force) in attempt to minimize the risk of injury (Biewener and Taylor, 1986; Farley and Taylor, 1991; Raynor et al., 2002). In horses the trot-gallop transition was not accomplished at the energetically optimal speed but at the speed where musculo-skeletal forces reached a critical level (Farley and Taylor, 1991).

Ground reaction forces have been studied at different speeds of walking and running by Nilsson and Thorstensson (1989). Differences in pattern and magnitude for the vertical ground reaction forces (GRF) were found as well as differences in anterioposterior and mediolateral impulses, which are larger in walking compared to running.

According to Hreljac (1993), who studied important variables of the horizontal and vertical GRF, GRF do not trigger human gait transition because they do not appeal to the four criteria of triggers (Fig. 5). The type of transition that is executed (walk-run versus trot-gallop) might explain the different finding for humans (Hreljac, 1993) and quadrupeds (Farley and Taylor, 1991). Furthermore, it is unlikely that humans would reach possible damaging levels at the low WRT-speed.

When starting to run in the WRT, Raynor et al. (2002) found an increase in time to first peak, which allowed forces to be absorbed over a greater period of time. Loading rate appeared as a possible trigger for WRT and RWT. Raynor et al. argued that WRT occurs when the elastic energy can be stored efficiently. RWT, on the other hand, would be the consequence of a lacking energy storage/recovery, favouring the energy exchange between gravitational and kinetic energy of the walking gait.

Li and Hamill (2002) described changes in vertical ground reaction forces in the last steps before transition on an accelerating treadmill. The results can be seen in figure 3 (p.15). However, these results did not offer insights in the possible determining character of the ground reaction forces as they were not obtained during and after transition.

Is it kinetic stress?

Humans do not change gait in order to decrease mechanical stress. But dynamic kinetic characteristics, like loading rate and time to first peak, could be of importance in driving gait transitions.

5. Vision and training status…

5.1 Vision, an extrinsic characteristic

Vision plays an important role in regulating locomotion. Humans receive information about the characteristics of the environment as well as information about how they are moving through this environment. Optical flow can have an important influence on whole body velocity in humans. Patla (1997) postulated that ex-proprioceptive information about self-motion is used on-line in a sampled control mode to control the speed of walking and running.

Mohler et al. (2004) were the first to investigate whether optical flow influences the walk-to-run (WRT) and the run-to-walk transition speed (RWT). Subjects who experienced optical flow that was faster than their locomotion speed, showed a significantly lower WRT- and RWT-speed. In contrast, subjects who experienced optical flow that was slower than their locomotion speed, showed a significant higher WRT- and RWT-speed. Apparently, transition speed is among others determined by the optical flow. Actually, this is not surprising as Lishman and Lee (1973) suggested that information from the visual system can override information from other sensor modalities.

The optical flow rate (and with this the perceived speed) appears as a determinant of gait transition speed. It could be that by successfully switching from one mode to the other the optical flow pattern at transition speed is stored in the coordinative structures shaping human locomotion.

5.2 Training status, an intrinsic characteristic

It is not unlikely that training status would have an influence on the transition speed, as training has an influence on energy consumption (usually higher VO2 max), internal work (by technique and experience) and muscle mass (Baechle and Earle, 2000).

Beaupied et al. (2003) theoretically calculated cross over points between (1) metabolic energy curves of walking and running (EOTS) and (2) external work curves of walking and running (MTS). The relation between EOTS en MTS differed depending on the training status of the subjects. One of the shortcomings in this research is that natural transition speed was not determined. Based on the theoretical outcome of Beaupied et al. (2003), Rotstein et al. (2005) examined transition speed of runners and non-runners and did not find any correlation between training status and transition speed.

In conclusion, training status is probably not influencing transition speed.

Opposed to the previous points that gave an overview of possible determinants of human gait transitions, the following points (6-7) give the reader an idea of how the human locomotor system handles all these determinants. Does human locomotion (involving gait transitions) occur automatically? In other words: does transition just happen as a consequence of the self-organisation of the system? Or is cognitive input necessary steering transition in the right direction?

6. It just happens?

According to the dynamical systems theory, transitions are automatic consequences of the collective structure of the human neuro-musculo-skeletal system (Diedrich and Warren, 1995; Abernethy, 2002; Fig. 2). It just happens!?!

When continuously changing the control parameter (e.g. speed) preservation of a gait pattern is maintained over a wide range of speeds. At transition speed, the coordination pattern becomes “unstable”, then suddenly jumps to the running attractor with a different but again relatively stable pattern. Speed is generally accepted as the control parameter for gait transitions. There is, however, much debate about the appropriate order parameter (Diedrich and Warren, 1995, 1998a, 1998b; Getchell and Whitall, 2004; Kao et al., 2003; Seay et al., 2006).

This sudden qualitative reorganization of the system is characterized by a loss of stability, which can be measured through critical fluctuations (increase in standard deviations) and critical slowing down (increase in time to recover from perturbation). Furthermore, there should be a tendency to stay in the basin of attraction, which results in hysteresis, i.e. WRT-speed differs from RWT-speed (Diedrich and Warren, 1995, 1998a, 1998b; Hanna et al., 2000). This paragraph shall describe the current status of the dynamical systems theory in research on human gait transitions.

The starting shot for implementing the dynamical systems theory in gait transition research has been given by Diedrich and Warren in 1995. They found a qualitative reorganization of the leg segments, reflected in a sudden change of relative phasing (ankle-knee and ankle-hip). On individual basis a hysteresis effect was found and loss of stability was indicated by an increase of the variability in the transition region. The authors manipulated the attractor layout by adding loads on the ankles and altering grade, which led to changes in the walk-run transitions.

Although Kao et al. (2003) found the same sudden reorganization of intralimb coordination, they disputed the findings of Diedrich and Warren because an increase in variability around the transition region was not found. Since this loss of stability (and consequently increase in variability) is an absolute prerequisite for a variable to be labelled an order parameter, another mechanism forcing gait transitions must be present.

Recent research by Seay et al. (2006) also questions the applicability of the dynamical bimanual coordination models to gait transitions after examining the coordination and coordination variability of inter- and intra-limb lower extremity segmental couplings. They remark that the protocol of Diedrich and Warren (using steady-state velocities) does not fully capture the true nature of transitions. Different lower extremity couplings responded differently on increasing velocities, at least indicating that human gait transitions are more complicated than bimanual finger transitions. They suggest taking a deeper look at the inter-limb couplings because these are more sensitive to gait perturbations (Haddad et al., 2006).

Does it just happen?

There are indications that transitions occur as a consequence of the intrinsic dynamics of a complex system by changing speed. However, the exact mechanism (order parameter?) or modelling (based upon bimanual transitions?) is not yet completely understood.

7. Cognitive steering?

Motor control is seen to be multi-levelled (Fig. 6) with intention (or more general cognition) capable of overriding or modifying the self-organising dynamics of the (loco)motor system (Abernethy et al., 2002; Daniels and Newell, 2003).

Abernethy et al. (2002) found that transition does not need additional attentional resources beyond those of walking or running, reinforcing the theory that walking, running and the transition between both are essentially automatic. Therefore, gait must be controlled sub-cortically and/or by self-organizing processes (central pattern generator, p. 5). Sustaining non-preferred walking (walking at speeds higher than WRT) demands extra attentional sources, whereas for non-preferred running at speeds in proximity of the preferred transition speed (running at speeds lower than RWT) this is not true (Daniels and Newell, 2003).

When offering subjects a secondary task (solving math problems), WRT-speed increases supporting the hypothesis that cognitive factors have an influencing role in human gait transitions (Daniels and Newell, 2003). Distraction by attentional focus on the math task mitigates physical sensations of effort, contributing to triggering WRT.

Does transition need a cognitive input?

Human gait transitions on a treadmill do not ask additional attentional resource. Cognitive factors, however, can have an influence on transition speed. One of the hypotheses is that a cognitive load can distract attentional focus from physiological cues.

Question 3: Why do humans switch from one gait to the other?

A straightforward answer is, despite the growing interest in human gait transitions, not available. Most likely human gait transitions are **not triggered by one factor** but by a multifaceted interaction of psychopysiological stimuli, a **pool of determinants**, shaping the coordinative structures of human gait. The nature of possible determinants are as well muscular (TA, SO, GA,…), mechanical (feautures of the inverted pendulum, elastic energy storage), kinetic (loading rate), dynamical (relative phasing?) as extrinsic (visual flow) but can always be overridden by cognitive input. Some variables can be excluded such as energetic optimization and correlation with anthropometry or training status.

How the system incorporates all these factors, is still to be discovered. Transitions are not in need for additional attentional resources giving an indication for **self-organizing dynamics** of the human locomotor system

AIMS AND SCOPE OF THE PRESENT RESEARCH

1. Aims

Although it has been postulated that understanding gait transition might gain insight in the key factors that shape human locomotion (Farley and Ferris, 1998), the transition phenomenon when actually accelerating or decelerating across transition speed remains a rather unexploited field of human locomotion (Hanna et al., 2000). One of the aims of the present research is to fill some of the lacunas in the existing literature on human gait transitions. More specifically, how do humans actually realize transition and why do humans switch at that specific instant?

In order to answer the first part of question, transition is examined during actual acceleration across transition speed. This allows for studying different steps in proximity of the transition step, defined as the first step with a flight phase in the WRT and the first step with a double stance in the RWT. It is clear that transition using the spatiotemporal definition (see p. 3-4) occurs in one step, but adaptations could be present before this transition step to prepare the system for the transition (‘pre’paration) or after the transition step to complete transition and to continue in a new stable gait pattern (‘post’paration).

In first instance the transition speed and the spatio-temporal factors *(Chapter 2)* constituting speed were examined as they learn us how humans approach transition and because they reflect the collective output of the system (Aerts et al., 2000). Since the amount of acceleration would be one of the factors for hysteresis (Li, 2000; Li and Hamill, 2002) different accelerations were incorporated in the first study. Acceleration magnitudes were chosen to include the acceleration at which the WRT-speed equals RWT- speed i.e. no hysteresis at 0.07 m s^{-2} as well as lower (0.05 m s^{-2}) and higher (0.1 m s^{-2}) values (Li, 2000).

In *Chapter 3* kinematics of unsteady accelerating locomotion across the transition speed from walking to running and vice versa were examined to get a clear view on the realization of transition. During transition, there has to be an evolution from one symmetrical gait pattern over an asymmetrical transition to another symmetrical pattern. Kinematics were studied in the transition zone when gradually changing speed in order to understand how symmetries and asymmetries evolve into each other (Seay et al., 2006). More-over, movement kinematics pre-eminently allow for detection of either a transition process (covering several steps) either a step-wise abrupt change.

To date, nothing is known about how precisely the behaviour of the centre-of mass (COM) changes at transition *(Chapter 4)* despites the common use of COM-dynamics to discern walking from running (see p. 4). Do the COM-dynamics gradually shift from the walking to the running state? In other words: does the characteristic vaulting pattern of the COM (inverted pendulum) flattens step by step when approaching the transition speed, to pass smoothly into the spring-like behaviour of the stance limb when running? Or, does a transition in a more mathematical sense exist, being characterized by a sudden and clear discontinuity in mechanical behaviour? As a result, we can examine whether the change in dynamics (from out-of-phase to in phase fluctuations of potential and kinetic energy of the COM) and the transition according the spatio-temporal definition (Alexander, 1989; Farley and Ferris, 1998) concur.

In *Chapter 5*, we took a closer look at the ground reaction forces (GRF) and the centre-of-pressure (COP) during WRT and RWT. As most of transition researches are executed on a treadmill, kinetics of gait transitions are rarely examined. However, GRF can be interpreted as a comprehensive reflection of the locomotor system, which could enhance our understanding in the mechanisms of gait transition (Li and Hamill, 2002).

Why do humans change their gait pattern? Gait transition is the result of a multifaceted interaction of psychophysiological stimuli or a pool of determinants (Daniels and Newell, 2003; Fig. 6, p. 18). From literature is known that the m. tibialis anterior could be a possible determinant of transition (Hreljac, 2001; Prilutsky and Gregor, 2001). What is the role of the m. tibialis anterior within this pool?

In *Chapter 6* fatigue is induced in the m. tibialis anterior to weaken this possible determinant making it the weakest link in the chain. Thereby it could influence transition speed and the spatiotemporal factors. More-over, electromyography of the tibialis anterior muscle might give insight in the mechanisms of the high local perceived exertion.

In the general discussion *(Chapter 7)* all these findings shall be integrated to give the reader a clear view on all aspects (spatio-temporal characteristics, kinematics, COM dynamics, kinetics and muscular factors) of the actual realization of transition during actual acceleration across transition speed.

2 Scope

Throughout this thesis, transition is studied in a “transition zone”, a broad range of steps before, at and after transition step. Subjects were selected on sex (female) and height (being minimal 1.65 m and maximal 1.75 m) to rule out any possible influence of height and leg length, although only weak correlations have been found between anthropometric variables and transition speed (Getchell and Whitall, 1997 and 2004; Hanna et al., 2000; Hreljac, 1995b; Raynor et al., 2002; Thorstensson and Roberthson, 1987). During the accelerations (decelerations) the subjects were given only few instructions. They only knew that the treadmill speed was constantly accelerated (decelerated) from a comfortable walking (running) speed to a comfortable running (walking) speed. No instructions were given in order not to affect the spontaneous transition of the subjects.

During the course of this PhD two major experiments were set out. The <u>first experiment</u> was executed on the treadmill that was accelerated/ decelerated with constant acceleration (0.1, 0.07, 0.05, -0.1, -0.07, -0.05 m s^{-2}). 20 active female subjects participated in the experiment. Simultaneously treadmill speed (5 Hz), high speed video images in the sagittal plane (200 Hz, focus on feet), 3D kinematic recordings (240 Hz, full body) and EMG (1000 Hz, 8 muscles) were recorded. During the first session anthropometry was precisely measured, followed by treadmill habituation and the transition protocol. The second session began with preparing the subjects, fatiguing the m. tibialis anterior and was finalised with the transition protocol (Fig. 8).

In first instance spatio-temporal parameters (*Chapter 2)* were examined. Since they revealed no influence of acceleration on the transition speed, we opted to study kinematics of one acceleration/ deceleration (*Chapter 3)*. EMG of the m. tibialis anterior was processed and a the effect of m. tibialis anterior fatigue on transition speed was examined. (*Chapter 6)*.

The second experiment was executed overground on a 50 metre long walkway. 10 active female subjects were asked to follow a ray of lights that was constantly accelerated. This resulted in an average acceleration of 0.17 m s^{-2} of the subjects. 3D kinematic recordings (240 Hz, full body), ground reaction forces (960 Hz, AMTI 2 metre force plate) and plantar pressure measurements (120 Hz, RsScan ®) were assessed (Fig. 8). Unfortunately, the synchronisation between the kinematic recordings and the force plate measurements failed due to technical and software problems. The centre-of-mass was calculated *(Chapter 4)* and ground reaction forces and plantar pressure measurements were studied *(Chapter 5)*.

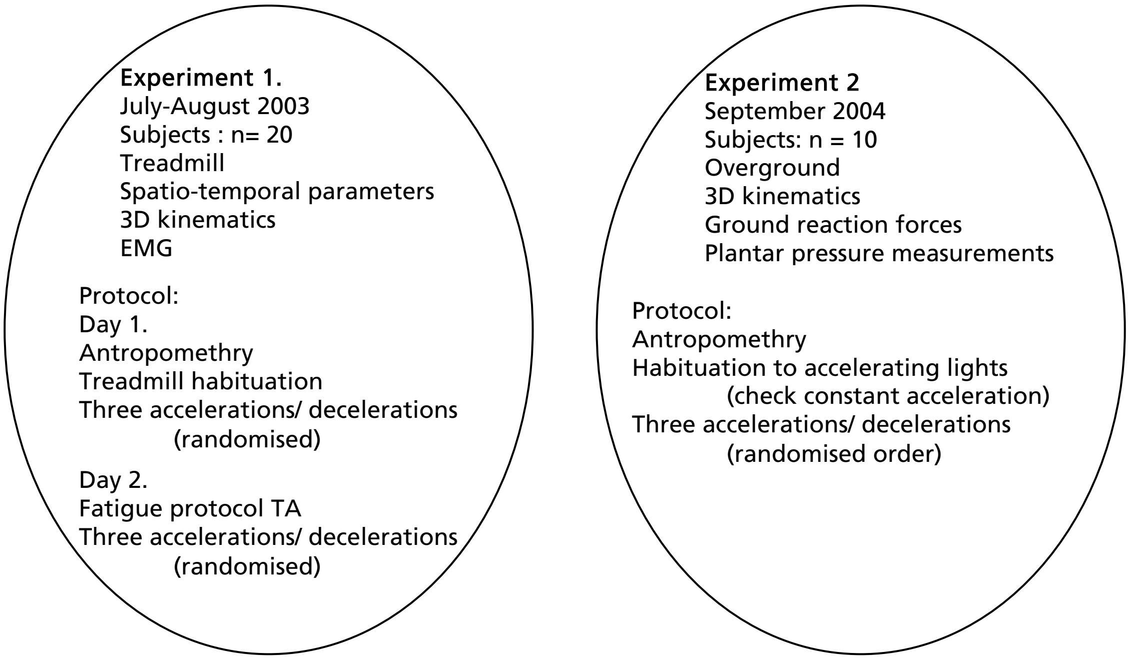

Figure 8. Shematic representation of the experiments.

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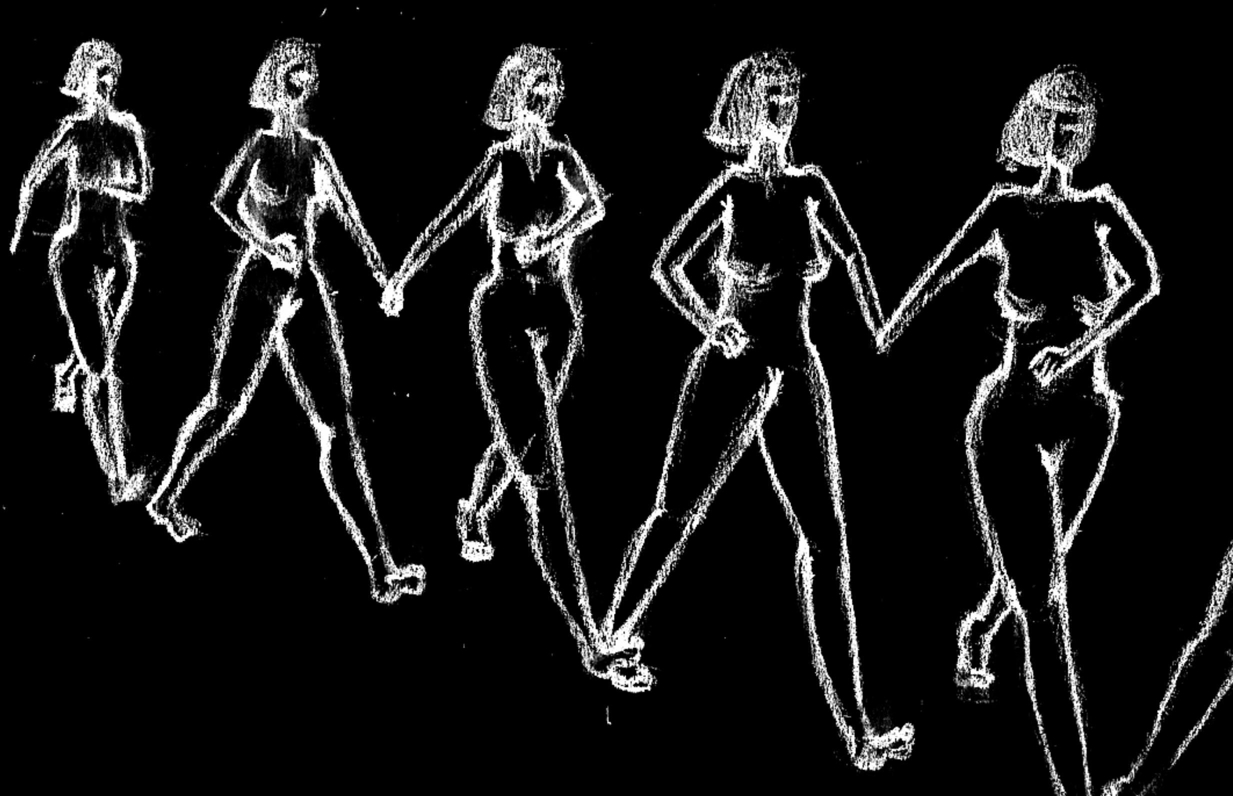
Chapter 2

Spatiotemporal characteristics of the walk-to-run and run-to-walk transition when gradually changing speed



ABSTRACT

The purpose of this study was to examine spatiotemporal parameters of the walk-to-run transition (WRT) and run-to-walk transition (RWT) when speed is altered with different constant accelerations. Twenty women (height: 168.9 ± 3.36 cm) performed three accelerations (0.05, 0.07 and 0.1 m s^{-2}) and three decelerations (-0.05, -0.07 and -0.1 m s^{-2}) on a motor-driven treadmill. The transition step in the WRT (first step with a flight phase) and RWT (first step with a double stance phase) occurred at the same speed for all accelerations but these did not occur in the same way. The most striking difference was the presence of a transition step with specific spatiotemporal characteristics in the WRT, whereas this was not observed in the RWT. The transition is not a sudden one-step-event. WRT occurred before transition and consisted of a ‘‘pre-transition period’’ and the transition step whereas RWT occurred after transition and consisted of the transition step and a ‘‘post-transition period’’. Both transition periods were characterized by an exponential evolution of step frequency and step length. Step frequency and step length showed a linear evolution before and after transition. The flight phase of the transition step in the WRT reached a minimum with comparable duration of the last flight phase in the RWT. The flight phase could be considered as an intrinsic dynamical factor of transition. Further research in kinematics, the trajectory of the body centre of mass and energy fluctuations will give more insight in these transitions.

Keywords: Gait transition; Spatiotemporal; Biomechanics

V. Segers, P. Aerts, M. Lenoir, D. De Clercq (2006)
Gait and Posture, 24, 247-254.
Available online (doi:10.1016/j.gaitpost.2005.09.006)

INTRODUCTION

Walking and running differ from each other in the absence or presence of a double stance phase and in the range of speeds (Getchell and Whitall, 2004; Titianova et al., 2004; Whitall and Caldwell, 1992). Walking has a double stance phase and is more commonly used at lower speeds of locomotion, while running is characterized by a flight phase and is used at higher speeds (Farley and Ferris, 1998; Getchell and Whitall, 2004; Winter, 1991). When changing speed, humans intuitively change from walking to running or vice versa (Thorstensson and Roberthson, 1987). The latter suggested that this transition is based on previous experience in combination with information from peripheral receptors and the activity in the central networks controlling locomotion.

Recently it has been suggested that locomotion is not strictly controlled by higher executive command structures (Davids et al., 1994). According to the dynamical systems approach, locomotion is a pattern emerging from all intrinsic, or physical, properties of the entire locomotion system interacting with the environment and specific task constraints (Diedrich and Warren, 1995, 1998; Li, 2000). Aerts et al. (2000) suggested that this largely self-organised system, or ‘‘integrated black box’’, determines the very specific combination of step frequency and length, i.e. the collective output of the system, at each speed. Changes in this system represent changes of the ‘‘integrated black box’’ or the descending modulation of that black box (Aerts et al., 2000; Li, 2000). Therefore, when gradually increasing the control parameter, e.g. speed, the organisational status of the system is preserved over a wide range of speeds, resulting in the typical walking pattern. However, as speed increases, the order parameter moves away from the walking attractor. This causes the organisational status to become “unstable” which is characterized by an increased movement variability (Diedrich and Warren, 1995, 1998; van Emmerick and van Wegen, 2000) At transition, the order parameter changes to the running attractor with a different, but relatively stable, pattern. Therefore, a transition can be seen as a discontinuity in gait (Alexander, 1989).

Most researchers believe that transition is an explicit event, based on findings in walking and running at different discrete constant speeds in the proximity of transition

(Abernethy et al., 2002; Getchell and Whitall, 1997; Hanna et al., 2000; Hreljac, 1995a, 1995b; Nilsson and Thorstensson, 1987; Raynor et al., 2002). Li and Hamill (2002), however, observed a gradual change in the ground reaction force pattern of the last steps before the transition point in a protocol with gradually changing speed. From that point of view, transition is no longer to be seen as an explicit event but merely as a process. At the transition point, duty factor (ratio of contact time and total stride time) immediately changes but it is not yet known whether or not an adaptation, to complete the transition, follows the transition point. A protocol with gradually changing speed is necessary to determine whether transition is an event or a process. A transition period should be studied to fully comprehend the transition phenomenon. This transition period comprises the transition point – defined as the first step with a flight phase (walk-to-run transition: WRT) or the first step with a double stance (run-to-walk transition: RWT) – together with a number of steps before and after the transition point. In earlier research acceleration was found to be an important task constraint, which influences WRT as well as RWT speed (Li, 2000). The amount of acceleration would be one of the factors for hysteresis (WRT speed differs from RWT speed) (Hanna et al., 2000; Li, 2000). Therefore, different accelerations were incorporated in current study.

The main purpose of this investigation was to describe and interpret spatiotemporal parameters of the walk-to-run and run-to-walk transition period when speed is altered with different constant accelerations. Our hypotheses were: (1) that a transition process is visible in the spatiotemporal characteristics of several steps before and after the transition point and (2) that the WRT is different from the RWT.

MATERIALS AND METHOD

1. Subjects

A group of 20 active, normal female human subjects participated in the study having given informed consent. Average values and standard deviations for age, height and mass can be found in Table 1.

Subjects were selected on sex, height, being minimal 1.65 m and maximal 1.75 m to rule out any possible influence of height and leg length, although only weak correlations have been found between anthropometric variables and transition speed (Getchell and Whitall, 1997; Hanna et al., 2000; Hreljac, 1995b, Raynor et al., 2002; Thorstensson and Roberthson, 1987). The ethical committee of the Ghent University Hospital approved the experimental protocol.

	X	SD
Height (cm)	168.9	3.36
Body mass (kg)	63.2	5.98
*Leg length (cm)**	91.4	1.80
Age (years)	24.5	2.76

Table 1. Subjects characteristics: mean (X) and standard deviation (SD) for height, body mass, leg length and age. * Leg length= distance trochanter maior- ground

2. Treadmill protocol

Before the tests all subjects were familiarised with the treadmill by using it for at least 15 min at different speeds (Wall and Charteris, 1980). Each subject performed 25 trials divided into five blocks of five trials with a rest period of 30 s between each block, after one familiarisation trial block. Each block was characterized by a specific constant acceleration and were 1P ($a = 0.1$ m s^{-2}), 5P ($a = 0.05$ m s^{-2}), 7P ($a = 0.07$ m s^{-2}), 1N ($a = -0.1$ m s^{-2}), 5N ($a = -0.05$ m s^{-2}) and 7N ($a = -0.07$ m s^{-2}). ‘P’ and ‘N’ indicate positive and negative acceleration, respectively, causing walk-to-run transitions (WRT) and run-to-walk transitions (RWT). By choosing these magnitudes, the acceleration at which the WRT speed equals probably the RWT speed, i.e. no hysteresis at 0.07 m s^{-2} (Li, 2000) is included as well as lower (0.05 m s^{-2}) and higher (0.1 m s^{-2}) values. The blocks were divided at random over the subjects but alternating a P with an N-block. The first block was considered a familiarisation trial block and was not incorporated in the calculations.

The speed of the treadmill was electronically registered (5 Hz) on-line and synchronized with video recordings by means of LEDs.

3. Video recordings

Sagittal plane films using a high-speed video camera (JVC DVL9800) at 200 frames/s were taken of all trials and focussed on the leg movements. The moment of initial contact and of final contact of the foot with the treadmill were determined from the video recordings (Wall and Crosbie, 1996) (maximal error = 0.01 s). This permitted the analysis of a step, the smallest functional physiological increment that represents changes in spatiotemporal output. The following spatiotemporal parameters were calculated (Zatsiorsky, 1994):

Duty factor (DF) = ratio of contact time and total stride time (period between two heel strikes of the same foot).

Step frequency (SF) = number of steps over a period of time, calculated as 1/Δt (Δt: time between two successive foot contacts).

Step length (SL) = distance travelled from heel strike of one foot to the heel strike of the other foot (treadmill speed divided by step frequency).

Double stance phase = period in a walking stride with both feet touching the ground.

Distance of double stance phase = double stance duration multiplied with the instantaneous speed of the treadmill.

Flight phase = period in a running stride with both feet in the air.

Distance of flight phase = flight phase duration multiplied with the instantaneous speed of the treadmill.

4. Statistics

All data were analysed using the SPSS 11.0 package. Descriptive statistics (mean - S.D.) were calculated for subject characteristics, speed (v), duty factor (DF), step frequency (SF) and step length (SL). The analyses to compare v, DF, SF and SL were done in a step-by-step manner. The transition step was named step zero (0) and defined as the first step with a flight phase when speed was increased (WRT) or the first step with a double stance phase when speed was decreased (RWT). Before transition, steps were given negative signs; steps after transition were given positive signs. For each condition the average of all successfully recorded trials (minimum three, maximum five) was used since intra-subject variability was low (see Results). Therefore, intra-class correlation coefficients (ICCs) were calculated separately for each individual and for every acceleration/deceleration. In the transition period (step -8 until step +8) a best fit through least squares regression (linear and polynome of second order) was calculated.

A two (negative versus positive acceleration) by three (high 0.1 m s^{-2}, intermediate 0.07 m s^{-2}, low 0.05 m s^{-2} acceleration) repeated measures analysis of variance (ANOVAs) was used to test the effects of sign and magnitude of the acceleration. A paired samples T-test was then used to examine the differences in duty factor, step frequency and step length between steps -1 and 0 and between steps 0 and +1. Slopes were calculated for every individual at each level. A two (before and after transition) - three (acceleration) repeated measures ANOVA was used to examine possible differences before and after transition and between accelerations in the WRT and in the RWT.

RESULTS

1. Intra-variability

The intra-variability was very low for speed, duty factor, step frequency and step length which was indicated by the high ICCs which were never lower than 0.93 for all subjects. Because of the high ICC, the average of each subject could be used instead of the separate trials. Intra-subject variability for step frequency is indicated in figure 1.

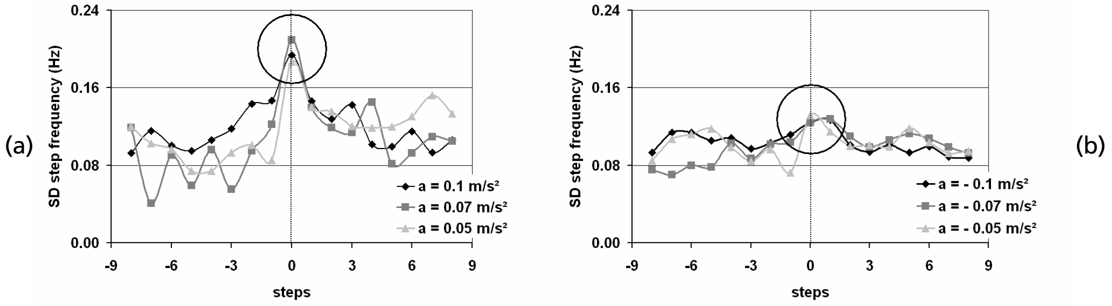


Figure 1. Intrasubject variability

The evolution of the intrasubject variability by means of the standard-deviation on step frequency in the (a) WRT and (b) RWT.

2. Transition speed

There was no significant difference for transition speed between the six different conditions (Table 2). Transition was not affected by the sign of acceleration ($F_{1,15}$ = 1.744; p = 0.206) nor by the magnitude of acceleration ($F_{2,30}$ = 1.981; p = .175). The repeated measures ANOVA did not reveal any interaction effect either ($F_{2,30}$ = .185; p = .832).

		Transition Speed (m s^{-1})	
	a (m s^{-2})	*X*	*SD*
WRT	0.1	2.16	0.12
	0.07	2.10	0.06
	0.05	2.12	0.08
RWT	- 0.1	2.19	0.14
	- 0.07	2.12	0.09
	- 0.05	2.17	0.06

Table 2. Transition speed: mean (X) and standard deviation (SD)

3. Duty factor

In the protocols with increasing speed, duty factor slightly decreased from step -8 until step -1 before transition in a linear fashion (Fig. 2a). In step -1, the duty factor then fell from approximately 0.58 to the significantly lower value 0.46 in the transition step (Table 3a), to decrease further significantly to 0.42 in step +1 after transition. After transition (step +1 until step +8) the duty factor slightly decreased (Fig. 2a). Slopes remained the same for all accelerations, but a significant difference was found between the slope before and after transition.

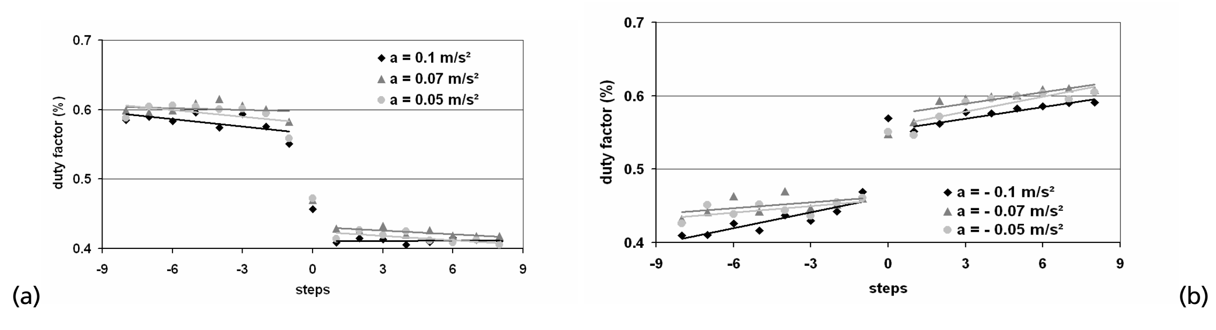


Figure 2. Duty factor

The evolution of mean duty factor in the (a) WRT and (b) RWT is represented.

The opposite was observed in the protocols with decreasing speed. Before transition, duty factor increased slightly, then suddenly increased significantly (Table 3a) from approximately 0.46 in step -1 to 0.55 in step +1 (Fig. 2b). There was no difference between the slopes before and after transition or between accelerations.

4. Step frequency–step length

In the WRT-protocol, the evolution of step frequency and step length in the last walking steps (Fig. 3) was best fitted with second order polynomes. The last two walking steps were characterized by an increased step frequency and decreased step length. Step frequency and step length in the transition step were significantly different from both the last walking and the first running step (Table 3b and c) showing a clear discontinuity in the collective output of the system. After transition, the spatiotemporal characteristics of the first running steps evolved in an opposite but linear way. A slightly decreasing step frequency and increasing step length was observed.

In the RWT-protocol (Fig. 4) step frequency and step length of the last running steps before transition had a linear evolution, whereas a second order polynome best described the evolution during the first walking steps after transition. Before transition there was a decrease in both step frequency and step length. The transition step was closely related to the last running step (step -1), as can be seen in Table 3. In comparison to the first walking step (step +1) the step frequency was altered. After transition there was a substantial decrease in step frequency and increase in step length. This latter increase reached a peak at step +4, with step frequency decreasing slightly and step length remaining relatively constant thereafter.

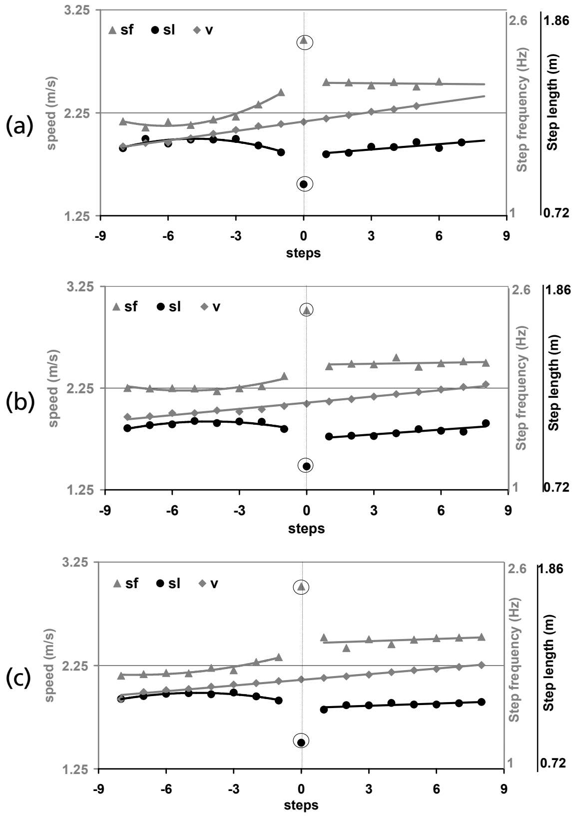


Figure 3. Spatiotemporal factors for the walk-to-run transition (WRT)

The evolution of mean step frequency (SF), mean step length (SL) and mean speed can be seen for the different accelerations

(a) 0.1 m s^{-2}, (b) 0.07 m s^{-2} and (c) 0.05 m s^{-2}.

Regression lines have R² values ranging between 0.27 and 0.86

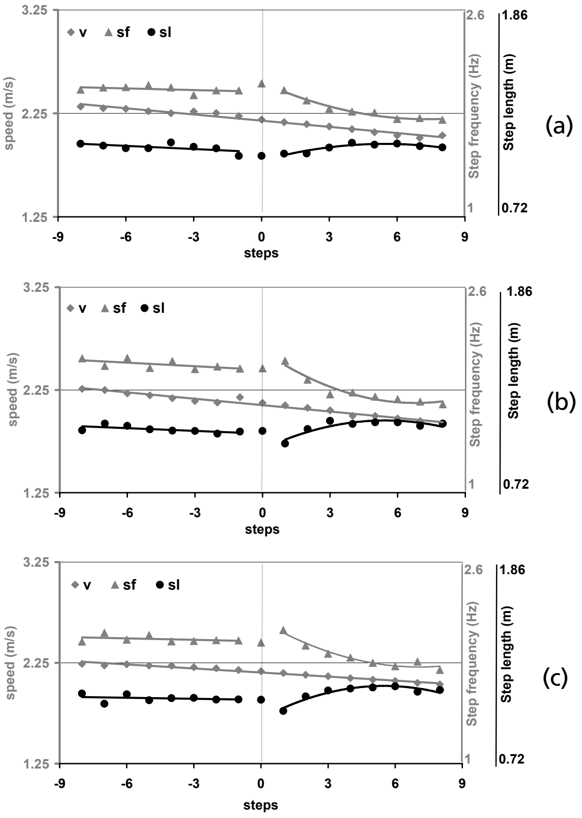


Figure 4. Spatiotemporal factors for the run-to-walk transition (RWT)

The evolution of mean step frequency (SF), mean step length (SL) and mean speed can be seen for the different accelerations

(a) -0.1 m s^{-2}, (b) -0.07 m s^{-2} and (c) -0.05 m s^{-2}.

Regression lines have R² values ranging between 0.26 and 0.97.

		Step-1					Step 0		Step+1				
		X	*SD*	*T**	*df**	*p**	*X*	*SD*	*X*	*SD*	*T^+*	*df^+*	*p^+*
(a) Results of paired sample T-test between steps 0, -1 and +1 for duty factor													
WRT	*0.1*	0.55	0.023	12.838	15	<0.01	0.46	0.034	0.41	0.034	5.062	15	<0.01
	0.07	0.58	0.013	17.309	15	<0.01	0.47	0.015	0.43	0.024	7.141	15	<0.01
	0.05	0.56	0.033	10.335	15	<0.01	0.47	0.028	0.41	0.024	6.27	15	<0.01
RWT	*- 0.1*	0.47	0.029	-13.181	16	<0.01	0.57	0.026	0.55	0.019	4.211	16	<0.01
	- 0.07	0.46	0.016	-8.146	16	<0.01	0.55	0.030	0.56	0.016	-1.306	16	ns
	- 0.05	0.46	0.017	1.57	16	ns	0.55	0.019	0.55	0.020	1.185	16	ns
(b) Results of paired sample T-test between steps 0, -1 and +1 for step frequency													
WRT	*0.1*	1.96	0.22	-10.15	15	<0.01	2.37	0.29	2.04	0.22	6.32	15	<0.01
	0.07	1.90	0.18	-14.17	15	<0.01	2.41	0.31	1.97	0.21	11.99	15	<0.01
	0.05	1.87	0.13	-12.29	15	<0.01	2.41	0.28	2.02	0.21	6.60	15	<0.01
RWT	*- 0.1*	1.98	0.17	-2.13	16	ns	2.03	0.19	1.98	0.19	1.39	16	ns
	- 0.07	1.97	0.16	-0.11	16	ns	1.97	0.19	2.03	0.19	-2.08	16	ns
	- 0.05	1.98	0.10	1.57	16	ns	1.96	0.20	2.06	0.17	-5.94	16	<0.01
(c) Results of paired sample T-test between steps 0, -1 and +1 for step length													
WRT	*0.1*	1.10	0.05	9.023	15	<0.01	0.91	0.07	1.09	0.03	-6.94	15	<0.01
	0.07	1.09	0.07	7.194	15	<0.01	0.87	0.12	1.04	0.07	-8.367	15	<0.01
	0.05	1.12	0.06	12.373	15	<0.01	1.12	0.06	1.07	0.08	-7.772	15	<0.01
RWT	*- 0.1*	1.12	0.07	3.532	16	<0.01	1.08	0.09	1.09	0.09	-0.598	16	ns
	- 0.07	1.08	0.08	-0.406	16	ns	1.09	0.05	1.02	0.07	6.58	16	<0.01
	- 0.05	1.11	0.06	0.358	16	ns	1.11	0.05	1.04	0.06	7.569	16	<0.01

Table 3. Average (X) and standard deviation (S.D.) for steps-1, 0 and +1

* Comparison between transition step and step -1.

$^+$ Comparison between transition step and step +1.

5. Flight phase and double stance

In WRT-protocol the last walking steps before transition had a reduced double stance. In the RWT-protocol flight phase also decreased before transition. There was no significant difference between the flight phase duration of the last step before transition in the RWT-protocol (Fig. 5b) and the first step after transition in the WRT-protocol (Fig. 5a). On the other hand the double stance of the last step before transition in the WRT-protocol (Fig. 5a) was significantly longer than the first double stance in RWT-protocol (Fig. 5b) in two of the three accelerations ($p < 0.01$).

In the WRT-protocol the flight phase of the transition step was significantly shorter than the double stance of step-1 and the flight phase of step +1. In the RWT-protocol the double stance of the transition step was shorter than the flight phase of step-1, before transition ($p < 0.01$; Fig. 5b). After transition there was a gradual increase in the duration of flight phase in WRT and of double stance in the RWT.

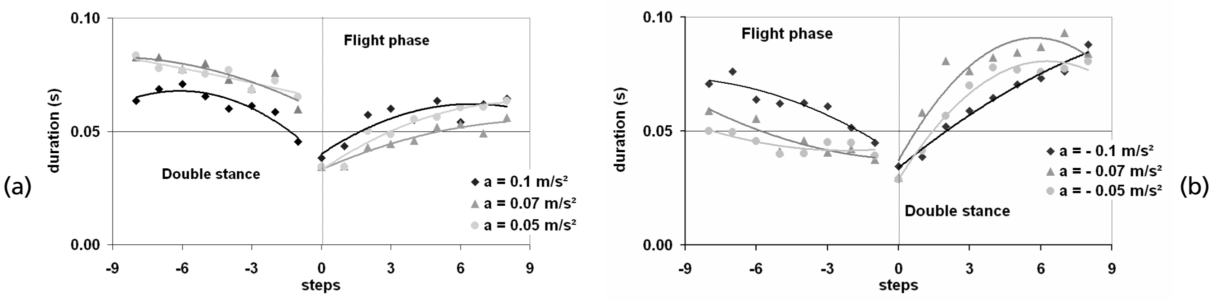


Figure 5. Duration of double stance phase and flight phase

Duration of flight phase and stance phase in the (a) WRT and (b) RWT for the three different accelerations/ decelerations. R^2 values for the regression line for flight phase vary between 0.89 and 0.97 in the WRT and between 0.05 and 0.16 in the RWT. R^2 values are low but the regression lines only have an illustrative value. An exponential relationship is chosen because linear regression had even smaller R^2 values. R^2 values for the regression line for double stance phase vary between 0.59 and 0.88 in the WRT and between 0.76 and 0.94 in the RWT.

DISCUSSION

A transition process was present in all accelerations and differences were observed between the WRT and the RWT indicating that our hypotheses were confirmed. This transition process seemed very stable since both intra- and inter-subject variability were low. Inter-subject variability was not reported separately but can be seen for the interval steps -1 to +1 in Table 3 and in figure 6.

1. Walk-to-run transition (WRT)

The second order polynome used in the regressions of step frequency and step length was found from step -8 to the transition step (Fig. 3), in contradiction to the linear evolution described previously (Grieve and Gear, 1966; Rosenrot et al., 1980; Winter, 1991; Zatsiorsky et al., 1994). To consider this further, we examined step frequency and step length in the interval steps -15 to -8, where a linear evolution of step frequency and step length was found (Fig. 6a). Due to technical limitations, recordings were limited to 8 seconds and data of the interval steps -15 to -8 were only available for six subjects.

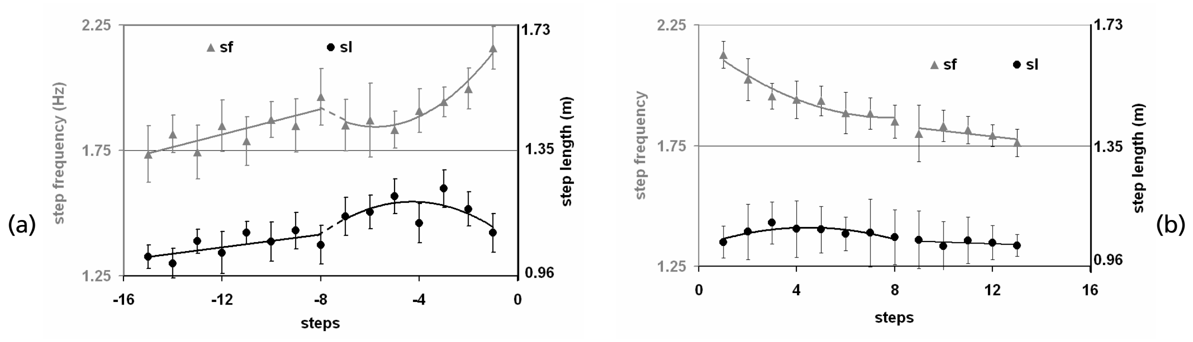


Figure 6. Evolution of step length and step frequency

(a) 6 subjects from 15 steps before transition in the WRT-protocol. R^2 for the lines of regression vary between 0.57 and 0.94.

(b) 5 subjects from transition in the RWT-protocol to 15 steps after transition with R^2 varying between 0.62 and 0.87.

WRT was not a sudden event but more of a process consisting of a ‘‘pre-transition period’’ and the transition step. The pre-transition period was situated from steps -8 to -1, since the linear evolution of step frequency and step length changed at that point into an exponential evolution. The R^2 values of the exponential regression were highest starting at step -8. Of importance is that a transition process exists, rather than knowing its exact starting point.

The most striking event in the WRT was the outlying transition step (Figs. 2 and 3, Table 3). Since it is the first step with a flight phase, the duty factor dropped below 0.5, and this step is different from the following running step. Moreover, step 0 was an outlier for step frequency and step length. Due to these specific spatiotemporal characteristics the transition step could neither be classified under walking nor under running and probably is a key factor in the conversion from walking to running. Because of the presence of a flight phase, this step was defined kinematically as a running step but this assumption should be regarded with caution as this step's spatiotemporal behaviour (duty factor, step frequency and step length) was significantly different from step +1 (Table 3).

After the transition point, when running, a linear evolution of step frequency and step length was observed, (Fig. 3) as expected in submaximal running (Cavanagh and Kram, 1990). Increase in speed was mainly due to a larger step length (Cavanagh and Kram, 1990; Dillman, 1975), and was accomplished mostly by the increasing distance covered during the flight phase.

Using the dynamical systems theory, it could be concluded that the walking pattern is drifting away from the walking attractor throughout the last steps before the transition step, where the control parameter, e.g. speed, reaches its critical value (Diedrich and Warren, 1995, 1998; Li, 2000; Li and Hamill, 2002; Raynor et al., 2002). The locomotion system moved through an unstable region, situated approximately between steps -8 and 0. The coordination pattern abruptly changed at the transition point to the running attractor (Diedrich and Warren, 1995, 1998). At critical values of the control parameter, the order parameter (step frequency) underwent a major change in value and was accompanied by an increased variability, as has been noted previously (Diedrich and Warren, 1995, 1998; Raynor et al., 2002). These so-called critical fluctuations are visible in figure 1a. The transition resulted in a rise in step frequency, a drop in step length and an increase in variability in line with the predictions of the attractor theory (Diedrich and Warren, 1995).

2. Run-to-walk transition (RWT)

The last steps before the transition step were characterized by a decrease in step length and a less pronounced decrease in step frequency. This linear evolution of step frequency and step length (Fig. 4) is in line with earlier findings of spatiotemporal characteristics of submaximal running (Cavanagh and Kram, 1990). The transition step follows the evolution of step length and step frequency of the last running steps.

Because of the presence of a first double stance, with a comparable duration of the last flight phase, the duty factor immediately rose above 0.5 (Table 3). As the system moved to the transition point the typical critical fluctuations were not observed, in contrast to the findings in the WRT (Fig. 1b). After the transition point, step frequency increased in the first walking step, then decreased exponentially in a period of 6–7 steps, and vice a versa for step length (Fig. 4). For the same reason as in the WRT, the period following the transition was examined (steps +8 to +15). This additional information was only obtained in five subjects because of technical limitations. Depending on the individual, the linear evolution of step frequency and step length started at steps +6 or +7 (minimum root mean square). The exact timing of the process is less important than the recognition of the existence of the RWT process, which consists of the transition step and a ‘‘post-transition period’’.

3. Transition step(s): functional hysteresis

In the present research, WRT and RWT speeds did not differ and different accelerations in both transitions did not lead to other transition speeds. This was in contrast with the findings of Li (2000) who identified acceleration as an important task constraint determining transition speed. The difference might be explained by the fact that acceleration is only one among many constraints, such as the chosen population. In the current study a homogeneous population of trained women was chosen to eliminate any bias that might be seen in the heterogeneous population studied by Li (2000).

In the present study no hysteresis in the strict sense of its definition was found as transition speed in the WRT and RWT protocols did not differ. However, a ‘‘functional hysteresis’’ was observed: WRT and RWT are realized another way. Firstly, we have shown that a transition step was present in WRT and not RWT. In line with the findings of Lee and Farley (1998), the transition step in the WRT might enable the locomotion system to accomplish the greater compression of the standing leg (more knee flexion).

Secondly, transition from one mode of locomotion to another took place in the walking steps close to transition as well in the WRT (before the transition point) as in the RWT (after the transition point). The spatiotemporal nature of the running pattern was more likely to be related to the unique step frequency–step length combination at each speed, even in proximity of the transition point, which could be interpreted as the strength of the running attractor. The term ‘functional hysteresis’ may be illustrated by considering comparisons between ‘equivalent’ steps. The first step with a flight phase in the WRT-protocol (step 0) was compared to step -1 in the RWT protocol and so on. The running steps did not differ. The walking steps in the transition period, on the other hand, showed significant differences, indicating that the adaptation to running (WRT) differed from the adaptation to walking (RWT).

4. Trigger

One intriguing question in gait transitions is to consider what triggers an alteration in a locomotion pattern? Hreljac (1995b) formulated four criteria in order to label a variable as trigger. The variable had to (1) change abruptly to a (2) different value at a (3) critical point that had to remain (4) constant in different conditions.

The flight phase reached a minimum at the transition point in both the WRT and RWT protocols. The last flight phase in the RWT-protocol was not significantly different from the first flight phase in WRT-protocol. The transition step was launched as soon as the minimal duration of flight could be generated in the WRT. Double stance appeared whenever the flight phase duration could not decrease any further in the RWT. The flight phase can be considered an intrinsic dynamical constraint of human locomotion (Rosenbaum, 1991; Kelso et al., 1994). It is likely that the integrated black box (Aerts et al., 2000) was then stimulated to undergo a modulation based on the intrinsic dynamical characteristic.

WRT and RWT do not occur at the same point in time and are more likely to be a process, as is the case in some animals (Rubenson et al., 2004; Verstappen and Aerts, 2000). The steps in the transition process have a double stance and an exponential evolution of step frequency and step length. A possible explanation could be that the system output adapts to produce the most efficient transition possible. However, it is not possible to explain fully the exact mechanism based on spatiotemporal factors alone. Further research in kinematics, the trajectory of the centre-of-mass and energy fluctuations in this transition zone might help a better understanding of the transition phenomenon.

In **conclusion**, the WRT and RWT processes were not the same. Adaptation to changing task constraints takes place primarily in the walking steps close to the transition both in WRT and in RWT and results in a pre- and post-transition period, respectively. In WRT an outlying transition step was observed, whereas no such step was seen in the RWT. The flight phase reached a minimum at the transition point and could be considered an intrinsic dynamical factor.

ACKNOWLEDGEMENTS

This research was supported by BOF–RUG B/03796/01–IV1. The authors acknowledge Ing. P. Van Cleven and Ing. D. Spiessens for data collection and technical support and Lic. A. De Cock for her professional advice. The authors also thank Prof. Dr. D. Adriaens (Ghent University, department of Vertebrate Morphology and Zoology Museum) for the use of the JVC high-speed camera.

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Chapter 3

Kinematics of the transition between walking and running when gradually changing speed

ABSTRACT

The purpose of this study was to examine kinematics of the walk-to-run transition (WRT) and run-to-walk transition (RWT) when speed is altered with a constant acceleration of 0.1 m s^{-2} respectively -0.1 m s^{-2}. Thirteen women (height: 168.9 ± 3.36 cm) performed gait transitions on a motor-driven treadmill. WRT-speed was 2.16 ± 0.12 m s^{-1}, RWT-speed 2.19 ± 0.12 m s^{-1}.

Kinematics were examined in the range from eight steps before to eight steps after transition in order to identify the possible occurrence of a transition process to facilitate the actual realization of transition.

A transition step in which the main changes from one gait to another are realized is present in WRT and RWT. Despite this clear discontinuity, a transition process also appeared in both transitions. In the WRT, transition was prepared and kinematic adaptations were found in the last swing before transition leading to altered landing conditions. During RWT post-transition changes were observed and RWT was only completed after reorientation of the trunk in the first walking stride after transition.

A noteworthy finding was that spatiotemporal (presence of a flight phase), kinematic (knee flexion) and energetic (kinetic and gravitational potential energy fluctuating in-phase versus out-of-phase) criteria to define transition stride correspond to each other. Furthermore, a functional interlimb asymmetry was recognized as a unique characteristic of the transition stride, offering a fourth way of identifying the transition stride.

Keywords: Kinematics; Gait transition; Walking; Running; Biomechanics

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Accepted for publication in 'Gait and Posture'

INTRODUCTION

To move from one place to the other, people walk at ease or run when in a hurry. These two gait patterns are characterized by their spatial and temporal symmetry, which is in contrast to other types of locomotion like skipping and galloping (Getchell and Whitall, 2004). Despite this similarity, walking and running manifestly differ in (1) their effectiveness in different speed ranges: walking at low speeds, running at higher speeds, (2) the involved fluctuations of gravitational potential and kinetic energy of the body's centre-of-mass (COM), which are organized out-of-phase in walking and in-phase in running and (3) their spatiotemporal characteristics reflected in the duty factor (DF = the fraction of the stride time a particular limb is in stance): permanent contact with the ground in walking (DF > 0.5) and flight phase with both feet leaving the ground in running (DF < 0.5: Farley and Ferris, 1998; Alexander, 2004). The latter two, the dynamical definition (2) and the spatiotemporal definition (3), are the two most common ways of defining walking and running. These two definitions usually, but not necessarily, coincide. Some birds, crabs, primates and elephant, for instance, show dynamic running, while still walking spatio-temporally (Rubenson et al., 2004), which is known as 'grounded running' (Rubenson et al., 2004) or Groucho running (Mc Mahon et al., 1987). In humans, it is still an open question whether gait discrimination according both definitions concurs or not. Besides this fundamental distinction, kinematic differences are reported as well, such as knee-angle, touchdown angle of the foot, etc. This offers the possibility to determine qualitatively whether people are either walking or running (Biewener et al., 2004; Novacheck, 1998).

Although it has been postulated that understanding gait transition might gain insight in the key factors that shape human locomotion (Farley and Ferris, 1998), the transition phenomenon when actually accelerating (walk-to-run transition = WRT) or decelerating (run-to-walk transition = RWT) across transition speed remains a rather unexploited field of human locomotion (Hanna et al., 2000). Up to date little is known about how humans realize the switch from one gait to the other (Abernethy et al., 1998; Diedrich and Warren, 1998; Li and Hamill, 2002; Segers et al., 2006;

Thorstensson and Roberthson, 1987). Therefore, it is essential to examine the kinematics of unsteady accelerating locomotion across the transition speed from walking to running and vice versa to gain the insights in how the neuromuscular system and the physical characteristics shape human locomotion, as put forward by Farley and Ferris (1998).

Available literature on accelerating across transition speed is scarce and not unequivocal. It might seem obvious that human gait transitions are realized in one step: humans walk or run (Raynor et al., 2002; Rubenson et al., 2004). Based upon the spatiotemporal definition using duty factor, there is a distinct difference: a flight phase is present or not and transition is realized in one step (Segers et al., 2006). However, Segers et al. (2006) showed that spatiotemporal factors change in a unique way in proximity of transition. In the WRT, this process occurred before the first step with a flight phase (spatiotemporal definition of WRT step) leading to a “pre-transition period”. The RWT-process, on the other hand, happened after transition consisting of the transition step (first step with a double stance phase) and a “post-transition period” (Segers et al., 2006). Such a gradual change was in agreement with the findings of Li and Hamill (2002), who took a closer look at the ground reaction forces prior to transition. The energy fluctuations of the centre-of-mass (dynamical definition), however, change abruptly in one single step from an in-phase to an out-of-phase organization during WRT (Segers et al., submitted).

Irrespective of the way one looks at transition, there has to be an evolution from one symmetrical gait pattern over an asymmetrical transition to another symmetrical pattern. Functionally, spatial and temporal asymmetry is an inherent feature of the transition stride because this stride includes a double stance and a flight phase, or one walking leg and one running leg (Getchell and Whitall, 2004; Seay et al., 2006; Segers et al., 2006).

In order to understand how these seemingly contradicting data about the nature of the transition event (gradual or not) fit each other and how symmetries and asymmetries evolve into each other, kinematics should be studied in a broad range of steps before, at and after transition in a protocol with gradually changing speed. Movement kinematics would allow for detection of either a transition process (covering several steps) either a step-wise change in kinematics. This could be important in understanding how the transition is realized on mechanistic, spatio-temporal and coordination level.

In the present study we wish to examine the realization (how) and nature (process versus event, symmetrical versus asymmetrical) of transition in a protocol with gradually changing speed with emphasis on movement kinematics. In this paper joint angles and angle-angle plots were chosen to allow the reader to get a clear view on the actual realization of the WRT and RWT. Our main hypotheses are that (1) there is a transition process covering multiple steps to change from one gait to the other, (2) regardless of this transition process a unique transition step can be identified and (3) the transition stride is characterized by a unique interlimb asymmetry.

METHODS

1. Subjects

A group of 13 active female subjects participated in the study after given informed consent. Mean and standard deviations for age, height and mass can be found in table 1. Subjects were selected on sex and height, being minimal 1.65 m and maximal 1.75 m to rule out any possible influence of height and leg length, although only weak correlations were found between anthropometric variables and transition speed (Getchell and Whitall, 1997, 2004; Hreljac, 1995). At the moment of the study all subjects were free from any disease or injury that could affect the results.

The protocol was approved by the ethical committee of the Ghent University Hospital.

	X	SD
Height (cm)	168.9	3.36
Body mass (kg)	63.2	5.98
*Leg length (cm)**	91.4	1.80
Age (years)	24.5	2.76

Table 1. Subjects characteristics

Mean (X) and standard deviation (SD) for height, body mass, leg length and age.

* Leg length= distance trochanter maior- ground

2. Treadmill protocol

As mentioned in the introduction, kinematics in a broad range of steps around transition should be studied. The utilization of a treadmill allows for such purpose. Furthermore, by using a treadmill, the acceleration imposed on the subjects can be regulated accurately. Prior to the tests all subjects were familiarized with the treadmill by performing treadmill (custom-built, 4kW, 3m x 0.6 m) locomotion for at least 15 minutes at different speeds.

Each subject performed at least three successful WRT and RWT trials (30s rest between each trial), randomly imposed to the subjects and characterized by an acceleration of 0.1 m s^{-2} respectively deceleration of -0.1 m s^{-2} (60s rest between acceleration/deceleration). This acceleration/deceleration is chosen because using this acceleration/deceleration led to the most pronounced differences in vertical ground reaction forces and spatiotemporal factors (Li and Hamill, 2002; Segers et al., 2006). The actual speed of the treadmill was on-line electronically registered (5Hz) and electronically synchronized with 3D kinematics.

3. Kinematic recordings

3D kinematic recordings were obtained at 240 Hz using 8 infrared cameras (Pro Reflex) and Qualisys software. A total of 66 markers (anatomical and tracking) were placed on the subjects. After a standing calibration trial, some of the anatomical markers were removed leaving 46 markers on the subjects. Afterwards, subjects started the treadmill protocol until at least three successful trials were recorded.

Marker placement was based on recommendations of McClay and Manal (1999). Anatomical markers were placed on the greater trochanter, the medial and lateral femoral condyles, the medial and lateral malleolus, the medial and lateral part of the calcaneus, on the first and the fifth metatarsal, the anterior superior iliac spice, the top of the acromion, the medial and lateral epicondyle of the humerus and on the styloid processes of the radius and ulna. Tracking markers consisted of a rigid plate secured to the thigh and the shank, markers on the calcaneus and on the top of the foot arch, a marker on the coccyx and on the seventh cervical vertebra and three tracking markers on the upper and lower arm.

4. Data Analysis

A 11-segmented model (feet, shanks, thighs, trunk, upper arms, lower arms) was developed to calculate the 3D joint coordinate system angles using Visual 3D (v3 19.0, USA). The three-dimensional motions of knee, ankle, hip and elbow were investigated through positioning of the segments with respect to each other; foot, shank and thigh with respect to the laboratory coordinate system (anteversion/retroversion). Joint rotation was calculated around the sagittal axis (flexion/extension). The HAT-segment was created in Visual 3D and axial rotation (yaw) and flexion-extension (pitch) were examined. Kinematic variables were studied within strides. Heel contact and toe-off were determined using the criteria proposed by Hreljac and Marshall (2000). They were validated using highspeed video images (200 Hz, camera JVC DVL9800) synchronized by means of LED-lights with the 3D recordings.

The transition step was defined as the first step with a flight phase when speed was increased (WRT) or the first step with a double stance phase when speed was decreased (RWT) and called step zero (0). Prior to transition, steps were given negative signs; steps after transition were given positive signs. To explore the possible presence of a transition process, kinematics were examined in the interval from step-8 to step+8 resulting in 16 steps and 8 strides. Consecutively, strides were normalized to 100%.

To explore the possible kinematic asymmetry of the transition step, a symmetry index (SI) was calculated. When plotting the position of the left to right segment, this resulted in a plot that can be mirrored around an axis of symmetry at 45° (Fig. 1). The SI was calculated by taking the mean of the position (anteversion-retroversion) of left and right segment over one normalised stride. If symmetry was present the ratio of both means was equal to 1 (Sadeghi et al., 2000).

The centre-of-mass (COM) was derived from the 11 segments using Visual 3D-software. First and second derivatives of these positions against time yielded velocities (horizontal: v_x, vertical: v_z) and accelerations (horizontal: a_x, vertical: a_z), respectively. Gravitational potential energy [$E_{pot} = mgh_i$; with m the mass of the subject, g the gravitational constant ($9.81 m\ s^{-2}$), h_i the instantaneous COM-height] and horizontal and vertical kinetic energy (Ekin = $mv_x^2/2$ and $mv_z^2/2$, respectively) fluctuations of the COM were determined with a moving coordinate system (speed of the treadmill belt).

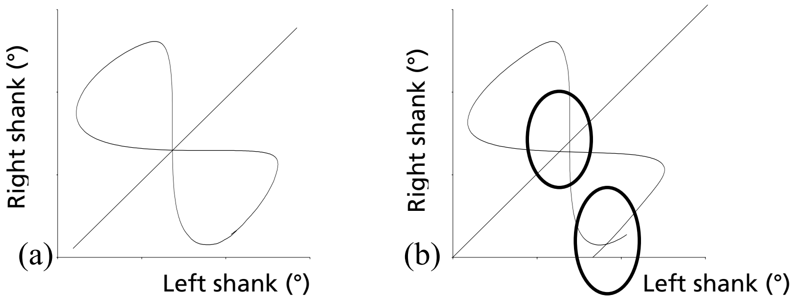

Figure 1. Symmetry index – interpretation
Average of left (X) and right (Y) shank for
(a) step+4 in the WRT indicating symmetry (SI = 1.043)
Image can be mirrored around the axis at 45°
(b) step 0 in the WRT indicating asymmetry (SI = 1.146, significantly different from 1)
Image can not be mirrored around the axis at 45° (see circles)

The authors are aware of the fact that accelerating on a treadmill and overground do not fully concur, since there is no actual overall acceleration or deceleration in the global reference frame. Yet, given a treadmill acceleration of only 0.1 m s^{-2} the missing inertial effect represent only a small fraction of the fore-aft forces (<5%). As a result, simple modelling showed that the 3D ground reaction force pattern experienced by the body when accelerating overground or when performing this acceleration on a treadmill are practically indifferent. Therefore, we concluded that the equations presently used are appropriate for estimation of the energy components of the COM.

5. Statistics

All data were analysed using the SPSS 12.0 package. Descriptive statistics (mean ± SD) were calculated for subject characteristics and for maximum (Max), minimum (Min), maximum stance (MaxS), minimum stance (MinS), range of motion stance (RomS), maximum swing (MaxSw), minimum swing (MinSw) and range of motion swing (RomSw) of each trial. The latter were examined in each transition protocol (WRT/RWT) separately by a repeated measures analysis of variance (ANOVA) with a Bonferroni test to compare all 8 strides pair wise. The same repeated measures procedure was used to examine functional differences between successive steps. Therefore, every ten percent of stance and swing was examined for foot, ankle, shank, knee, thigh, hip and elbow. This offered the possibility to compare stance and swing (identical functional phases) in walking and running (Table 2).

A paired sample T-test was used to compare Max, Min, and HC of similar steps in the WRT and RWT. By example: stride-6 in the WRT was compared to stride+6 in RWT. This offered the possibility to explore differences in the realization of WRT and RWT. A one-sample T-test was used to explore if the SI was significantly different from 1.

RESULTS

Transition speed was 2.16 ± 0.12 m s^{-1} for the WRT and 2.19 ± 0.12 m s^{-1} for the RWT. Transition speeds did not differ.

Few differences were found in kinematics among the walking strides and among running strides. Therefore, in results, focus is placed upon the differences between walking strides (WS) and the transition stride (TS) and between running strides (RS) and the TS.

1. Lower limb (Figs. 2, 3 & 5, Tables 2-4)

There was a distinct difference between walking and running in all observed lower limb variables. Statistical analyses were done to explore functional differences between the TS & WS and TS & RS at every 10% of stance and swing (Table 2).

WRT

Lower limb kinematics in the interval step-8 to step+8 during the WRT are given in figure 2. Characteristics of the TS are in between the two intrinsic gait patterns evolving from the walking to the running configuration in the WRT during the course of the step (Fig. 5). The transition is functionally already realized after the first half of stance (Table 2a). Afterwards no differences were found between TS and RS.

Maxima, minima and ROM can be found in table 3. As can be seen during stance most differences in MaxS, MinS and RomS occur between WS and RS and between WS and TS. However, the minima for foot, shank and thigh of the RS also differ from the

TS, resulting in differences for RomS of shank and thigh. During swing fewer differences are found and the TS evolved to the RS as no differences appeared.

At heel contact more hip (Fig. 2e) flexion is observed but due to the small difference in hip angle and the rather large standard deviation no significant differences were found. The ROM however is larger during RS and TS compared to WS in both stance and swing phase.

As mentioned before, among WS and RS no kinematic differences were found with exception of the following. During the last 10-20% of swing phase in the last WS differences with preceding WS appeared for shank (more anteversion), knee (more flexion) and hip (more flexion).

RWT

Figure 3 gives a representation of the lower limb kinematics from step-8 to step+8 in the RWT. Characteristics of the TS are in between the two intrinsic gait patterns evolving from the running to the walking configuration in the RWT during the course of the step (Fig. 5). On lower limb level, transition is realized after stance as no differences between TS and WS can be found during swing (Tables 2b & 4).

Maxima, minima and ROM can be found in table 4. As can be seen during stance differences in MaxS, MinS and RomS occur between all steps (a,b,c in last column of table 4a). The TS clearly is an intermediate, differing from both WS and RS. During swing fewer differences are found and the TS evolved to the WS as no differences with WS appeared. Interindividual variation for the hip angle was high and did not allow for differences.

Among WS no differences were found but among RS differences were found between the last RS and the preceding RS during swing: the foot configuration during midswing (more retrograde from 40 to 80% swing) and shank (more retroversion) and thigh (more retroversion) configuration from 80 up to 90% of swing.

		(a) WRT		(b) RWT	
		Stance	*Swing*	*Stance*	*Swing*
Ankle	WS • RS	0-70, 90-100	30-40, 70-100	0-70	20-30
	WS • TS	10-70	30-40, 70-100	30-100	30-40
	RS • TS	0-40	-	0-40, 60-90	-
Knee	WS • RS	0-80,100	0-20, 40-100	20-80, 100	0-20, 40-80
	WS • TS	0-80,100	0-20, 40-80, 100	30-80, 100	0-20, 40-80
	RS • TS	10-20	-	30-50	-
Foot	WS • RS	0,100	0-10, 30-80, 100	0-40, 90-100	0-10, 30-100
	WS • TS	100	0-10, 30-80, 100	60-100	0-10, 30-80
	RS • TS	0-30	-	0-40, 60-90	-
Shank	WS • RS	0-70, 90-100	0-10, 30-100	0-70, 90-100	0-10, 30-100
	WS • TS	0-40, 90-100	0-10, 30-100	0, 40-70, 90-100	0-10, 30-100
	RS • TS	0-50	-	0-70	-
Thigh	WS • RS	0,40-80,100	0, 20-60, 80-100	0-10, 30-100	0-100
	WS • TS	20-80, 100	0, 20-100	30-70, 100	10-100
	RS • TS	0-50	-	0-10	-

Table 2. Functional kinematic differences

Functional differences were explored at each 10% of stance and swing after normalizing stance and swing (to 100%).

Significant ($p<0.05$) differences (repeated measures ANOVA + Bonferroni test) during stance and swing in WRT and RWT are indicated between WS and RS (WS↔RS), between WS and TS (WS↔TS) and between RS and TS (RS↔TS). For the hip few differences were found and are mentioned in the text (Results).

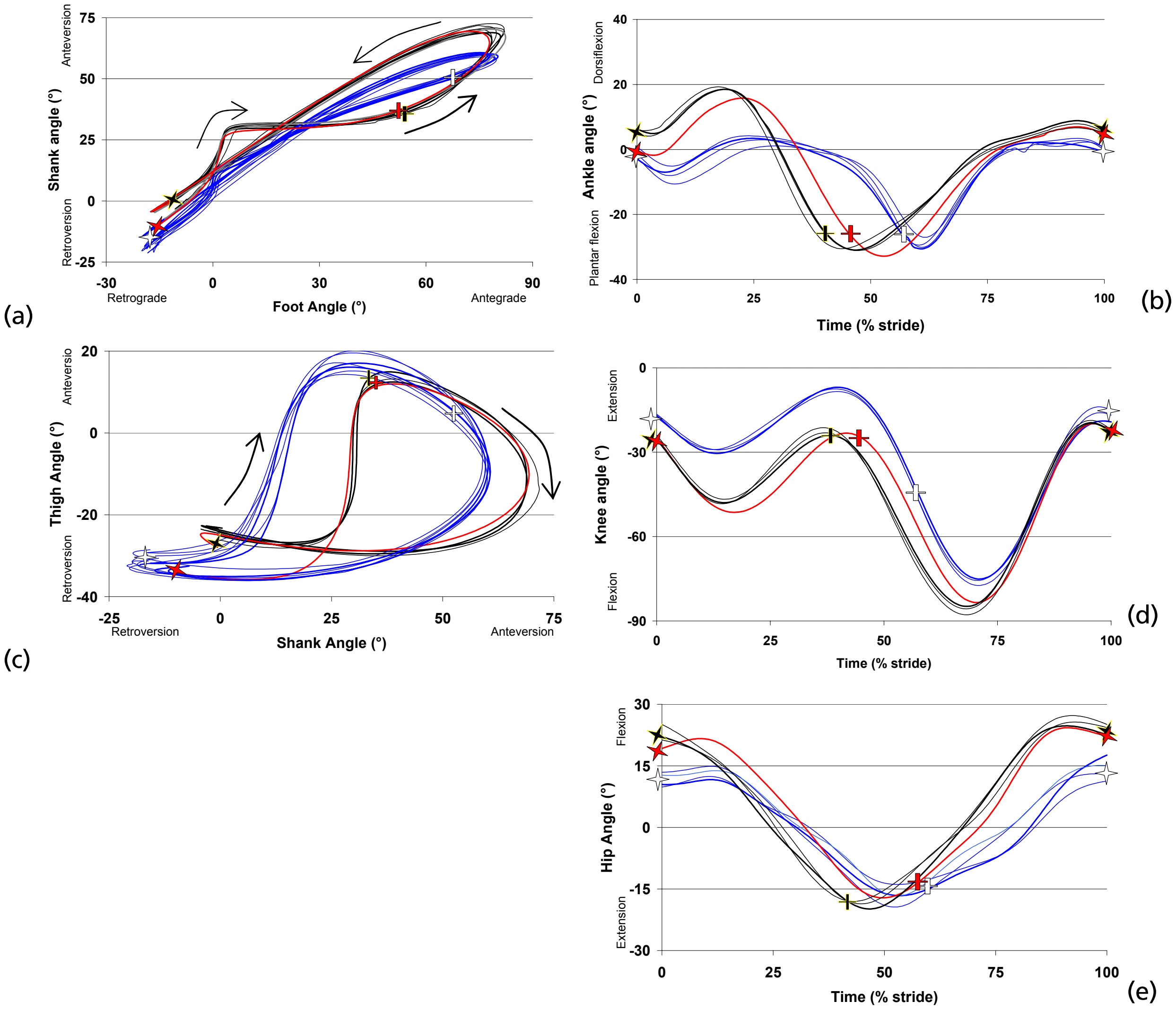

Figure 2. Lower limb kinematics of the WRT.

(a) Angle-angle plot of Foot angle (X-axis) versus Shank Angle (Y-axis)
(b) Ankle angle
(c) Angle-angle plot of Shank angle (X-axis) versus Thigh Angle (Y-axis)
(d) Knee angle
(e) Hip angle

Left plots (a,c) are angle angle plots of two adjacent segments. Right plots (b,d,e) are joint angles on a time basis with time normalized to stride duration. Black lines represent running strides, blue lines walking strides and the red line the transition stride. Stars indicate heel contact and crosses indicate toe-off (red – TS, yellow, RS, white WS).

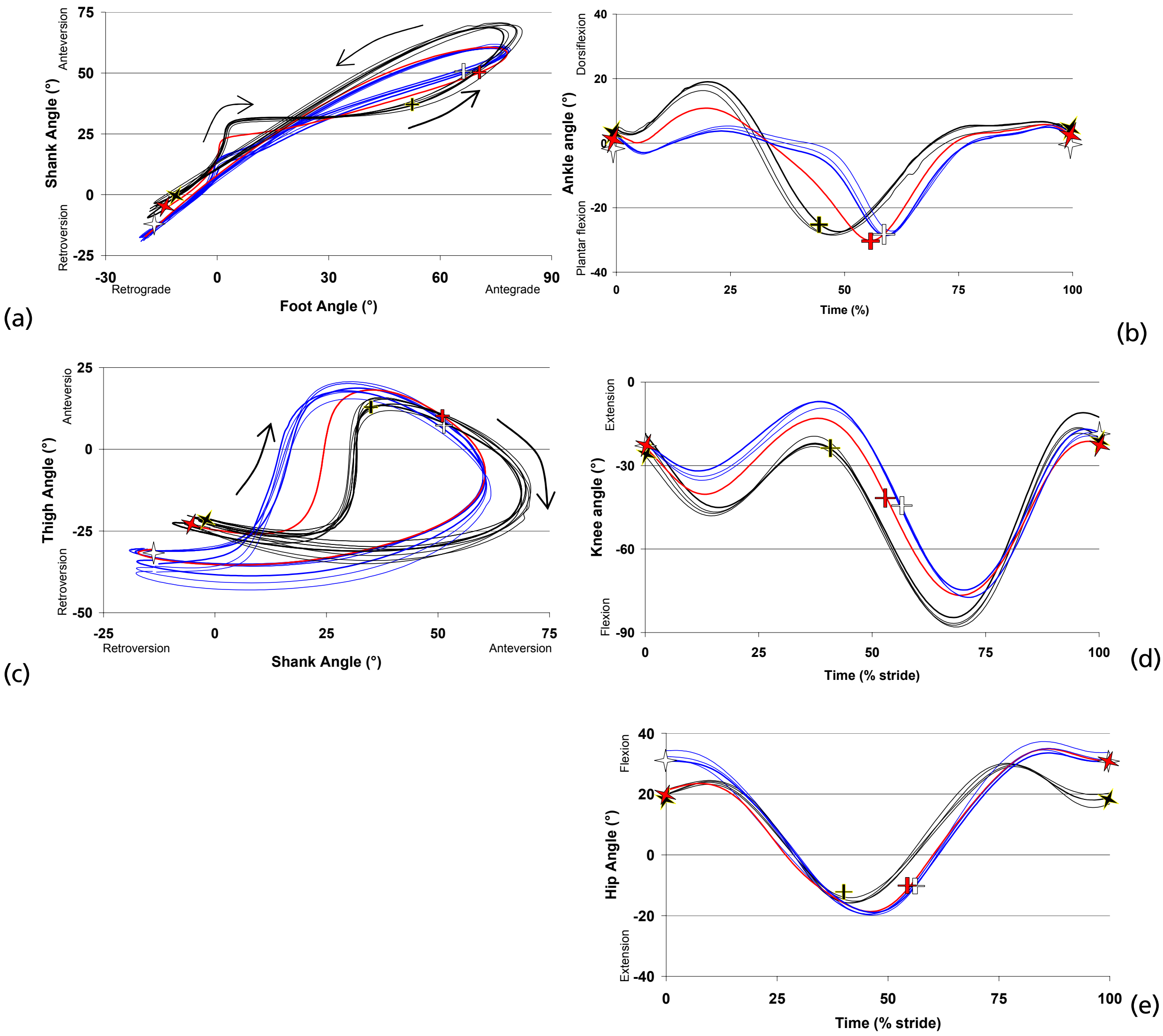

Figure 3. Lower limb kinematics of the RWT.

(a) Angle-angle plot of Foot angle (X-axis) versus Shank Angle (Y-axis)
(b) Ankle angle
(c) Angle-angle plot of Shank angle (X-axis) versus Thigh Angle (Y-axis)
(d) Knee angle
(e) Hip angle

Left plots (a,c) are angle angle plots of two adjacent segments. Right plots (b,d,e) are joint angles on a time basis with time normalized to stride duration. Black lines represent running strides, grey lines walking strides and the red line the transition stride. Stars indicate heel contact and crosses indicate toe-off (red – TS, yellow, RS, white WS).

<u>HAT</u> *(Head-Arms-Trunk segment)* (Figs. 4 & 5)

WRT

The trunk axial rotation (ROM) was larger during the RS compared to WS and TS (see Fig. 4a). TS started at values in between those of walking and running. After 20% of stance rotation in the TS equals the rotation during the RS. Differences with the WS remained, with exception intervals, where the curves cross. During swing trunk rotation during the TS is comparable to the RS but significantly smaller compared to the WS.

During stance of the TS, trunk angle (retroversion/anteversion) is different from RS and WS (Fig. 4c and 5). During swing, these differences with RS disappeared whereas differences with WS lasted with the trunk being more flexed during TS. During the last WS the trunk inclined more during swing compared to previous WS.

More flexion in the elbow (Fig. 4e) was observed during RS compared to WS. During the course of the TS the elbow gradually flexed more. Significant differences of the TS with WS were found throughout the complete stride whereas with the RS only during stance differences were observed.

RWT

Compared to walking the trunk had a larger rotation only during the first third of stance of the TS (Fig. 4b). Afterwards it was characterized by a small amount of trunk rotation, significantly different from the larger rotation observed during running.

The ROM of the trunk angle is significantly smaller during the RS compared to the WS and TS. As can be seen in figures 4d and 5, the trunk is more inclined in the running steps. Among WS differences in trunk anteversion were found between the first WS and the following WS (throughout whole stride except at 50% stance and 0-20% of swing).

The elbow is more flexed in the RS compared to the WS (Fig. 4f). The elbow configuration at heel contact of the TS is intermediate the walking and running configuration. Gradually the elbow extended and at 30% of swing, the elbow angle in TS was no longer significantly different from the WS.

		(a) WRT Stance											(b) WRT Swing										
		WS			*TS*		*RS*			*Stat*			*WS*			*TS*		*RS*			*Stat*		
		Mean	SD*	SD°	Mean	SD*	Mean	SD*	SD°	p	η^2	Bonf	Mean	SD*	SD°	Mean	SD*	Mean	SD*	SD°	p	η^2	Bonf
Ankle	*Max*	3.09	2.9	0.5	15.9	4.1	17.6	4.9	0.4	0.000	0.837	a,c	73.2	3.8	0.2	78.9	4.4	79.3	4.9	1.9	0.000	0.447	a,c
	Min	-28.1	6.3	0.3	-25.9	6.5	-27.7	7.5	0.9	0.685	0.024		41.3	6.0	1.0	38.3	7.9	38.9	8.9	1.1	0.079	0.052	
	ROM	31.2	7.4	0.7	41.7	7.1	45.3	8.2	0.5	0.000	0.481	a,c	32.0	7.1	0.9	40.5	7.5	40.4	8.9	2.7	0.000	0.324	a,c
Foot	*Max*	66.1	6.9	0.8	49.9	9.0	48.7	9.7	0.2	0.000	0.631	a,c	16.7	4.5	0.5	19.0	9.6	19.3	11.2	0.7	0.262	0.035	
	Min	-18.2	3.1	0.3	-16.5	4.1	-13.1	3.9	0.5	0.000	0.466	b,c	-83.8	3.2	3.5	-79.6	3.8	-79.1	4.3	0.5	0.000	0.182	c
	ROM	84.2	6.7	0.7	66.4	8.0	61.8	9.1	0.7	0.000	0.935	a,c	98.5	5.5	0.5	98.6	9.2	98.4	12.4	1.2	0.898	0.067	
Shank	*Max*	50.3	4.7	0.7	36.1	5.7	34.3	4.6	0.6	0.000	0.791	a,c	60.2	3.3	0.0	69.8	8.3	71.1	6.6	1.7	0.000	0.515	a,c
	Min	-17.3	3.1	0.6	-10.4	4.7	-1.4	3.5	0.4	0.000	0.850	a,b,c	-17.9	4.6	3.0	-4.7	4.1	-4.4	4.8	0.3	0.000	0.748	c
	ROM	67.4	4.6	1.2	46.5	5.2	35.7	5.3	0.9	0.000	0.934	a,b,c	78.1	4.3	3.0	74.4	6.1	75.4	5.4	1.5	0.000	0.727	c
Knee	*Max*	17.8	5.7	1.4	13.0	6.5	13.6	6.1	0.5	0.000	0.145	a,c	6.1	7.0	1.4	13.5	5.7	15.2	5.3	1.2	0.000	0.410	
	Min	-30.2	7.8	1.4	-34.0	7.6	-25.6	7.5	1.1	0.000	0.226	a,c	-35.5	8.0	0.7	-29.0	7.5	-30.3	9.2	1.2	0.000	0.176	a,c
	ROM	48.0	6.4	1.0	47.0	8.1	39.2	8.9	1.6	0.000	0.319	c	41.6	6.7	0.8	42.5	8.6	45.4	9.1	1.6	0.000	0.103	a,c
Thigh	*Max*	-3.8	6.2	1.8	-18.9	8.1	-14.9	6.6	0.6	0.000	0.526		-12.4	9.0	3.3	-14.8	7.1	-14.19	8.7	1.2	0.000	0.098	a,c
	Min	-43.2	9.7	2.3	-55.1	13.6	-47.3	8.4	0.7	0.000	0.184	b,c	-75.2	7.4	0.6	-83.7	11.8	-89.0	14.9	2.0	0.000	0.308	a
	ROM	39.4	7.7	0.8	36.2	10.3	32.4	6.7	1.2	0.000	0.191	b,c	62.8	5.9	3.7	68.9	8.3	74.9	11.6	1.4	0.000	0.338	

Table 3. Comparison of maxima, minima and range-of-motion (ROM) in WRT

Comparison of maxima, minima and ROM during stance (a) and swing (b) of lower limb variables in the WRT

SD* = average of standard deviations between subjects of similar steps (WS, RS, TS)

SD° = standard deviation between similar steps (WS, RS)

Bonf = Results of post hoc Bonferroni test with

a indicating significant differences between all WS with TS,

b indicating significant differences between all RS with TS

c indicating significant differences between all WS and all RS.

		(a) RWT Stance											**(b) RWT Swing**										
		WS			*TS*		*RS*			*Stat*			*WS*			*TS*		*RS*			*Stat*		
		Mean	SD*	SD°	Mean	SD*	Mean	SD*	SD°	p	η^2	Bonf	Mean	SD*	SD°	Mean	SD*	Mean	SD*	SD°	p	η^2	Bonf
Ankle	*Max*	17.1	4.4	1.0	10.7	6.5	4.6	4.4	0.9	0.000	0.670	a,b,c	76.9	4.6	0.5	74.5	5.2	74.3	4.5	0.3	0.001	0.098	
	Min	-23.8	7.1	0.5	-29.9	6.9	-26.2	8.2	0.9	0.002	0.087		41.0	7.4	1.2	40.6	5.4	42.5	7.0	0.8	0.382	0.029	
	ROM	40.3	7.6	0.4	40.6	10.2	30.8	9.8	0.1	0.000	0.277	a,b,c	35.9	6.6	0.9	34.9	7.4	31.8	8.0	1.1	0.003	0.088	
Foot	*Max*	47.9	7.6	1.3	69.5	7.4	67.5	8.8	0.2	0.000	0.658	b,c	18.5	7.7	2.0	17.6	4.1	16.3	4.5	0.8	0.007	0.078	
	Min	-13.0	3.8	0.3	-14.5	4.1	-18.2	2.6	0.2	0.000	0.434	a,c	-79.3	4.6	0.8	-81.7	3.2	-82.4	2.7	0.4	0.000	0.187	c
	ROM	60.9	6.4	1.0	84.0	8.0	85.6	9.4	0.0	0.000	0.732	b,c	97.8	7.7	1.4	99.3	4.4	98.6	5.4	0.4	0.422	0.027	
Shank	*Max*	35.9	4.8	1.1	50.4	5.2	51.8	4.2	0.7	0.000	0.787	b,c	70.1	6.6	0.9	61.4	3.7	60.5	3.6	0.4	0.000	0.541	b,c
	Min	-1.7	4.1	0.5	-5.9	5.4	-14.8	6.2	0.8	0.000	0.639	a,b,c	-8.2	4.3	2.4	-16.3	7.5	-18.9	6.7	0.8	0.000	0.514	b,c
	ROM	37.5	4.2	1.5	56.2	5.2	66.4	5.5	1.5	0.000	0.907	a,b,c	78.3	5.3	1.7	77.7	7.0	79.4	6.0	0.6	0.195	0.057	
Knee	*Max*	12.6	7.1	0.9	17.4	6.9	18.9	7.0	0.8	0.000	0.183	a,b,c	13.6	6.1	1.8	8.1	6.1	6.6	5.8	1.1	0.000	0.286	
	Min	-28.1	7.3	0.2	-28.0	7.0	-33.4	6.8	0.3	0.000	0.159		-32.8	7.1	1.2	-38.1	5.0	-37.5	6.2	1.4	0.000	0.171	b,c
	ROM	40.6	7.8	0.9	45.4	7.7	52.3	7.7	0.5	0.000	0.354	b,c	46.4	7.6	0.6	46.1	6.6	44.2	5.9	0.3	0.168	0.037	b,c
Thigh	*Max*	-17.7	9.3	0.5	-10.2	8.4	-4.7	8.0	0.7	0.000	0.417	c	-13.3	9.9	1.0	-15.5	10.0	-12.3	10.6	1.5	0.385	0.025	b,c
	Min	-49.0	12.5	0.9	-44.30	12.4	-44.1	11.9	1.4	0.000	0.101	a,c	-88.7	20.4	1.7	-74.7	15.3	-74.3	15.2	1.0	0.000	0.344	b,c
	ROM	31.4	8.0	0.6	34.1	8.4	39.4	9.8	1.1	0.000	0.251	a,c	75.4	16.3	0.8	59.2	11.8	62.0	11.3	0.4	0.000	0.735	

Table 4. Comparison of maxima, minima and range-of-motion (ROM) in RWT

Comparison of maxima, minima and ROM during stance (a) and swing (b) of lower limb variables in the RWT

Legend, see Table 3

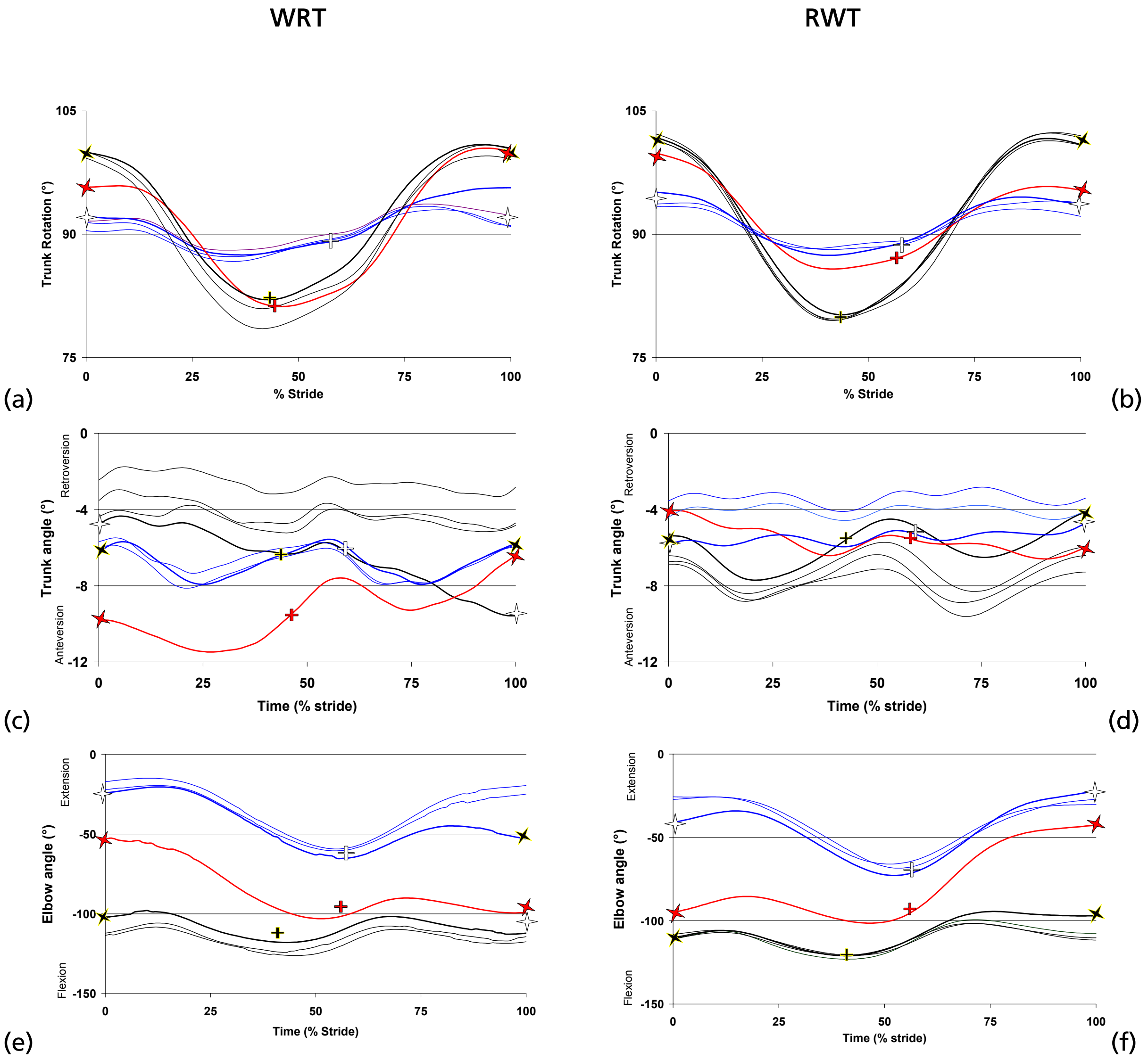

Figure 4. Kinematics of the HAT for the WRT and RWT

(a,b) Trunk axial rotation angle (yaw rotation angle) (c,d)Trunk anteversion/retroversion angle (pitch rotation angle) and (e,f) Elbow angle as a function of time normalized to stride duration. Left column represents the evolution of the HAT for the WRT and the right column for the RWT.

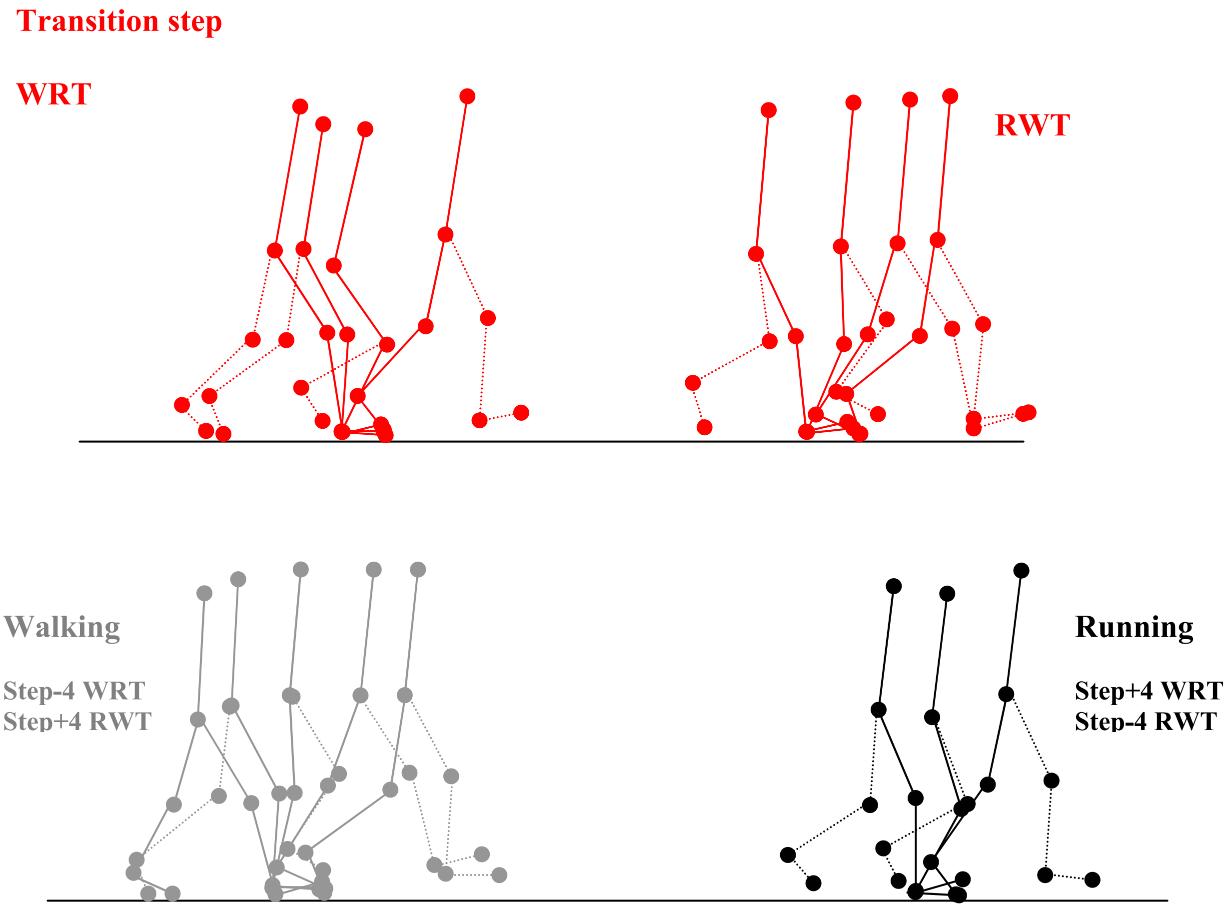

Figure 5. Stick figure of the actual realization of transition
Average kinematics of a walking stance phase (step-4), the transition stance phase (step 0) and a running stance phase (step+4). The grey line represents the walking step, the red line the transition step (upper panel = WRT, lower panel= RWT) and the black line the running step. Crucial events in the stance phase are represented: heel contact, contralateral toe-off (in case of WS and TS in WRT), midstance, contralateral heelcontact (in case of WS and TS in RWT) and toe-off.

3. Interlimb coordination (Table 5)

A symmetry index (SI) was calculated to explore differences between left and right limb. If SI was significantly different from 1, left and right segment do not perform symmetrical actions. As can be seen in table 5, asymmetry is found for the foot during TS of WRT, for the shank during the TS of WRT and RWT, for shank and thigh during the first WS in the RWT, for thigh during TS of RWT and for the thigh during the last WS in the WRT.

	Foot			Shank			Thigh		
Stride	*Mean (SD)*	*t*	*p*	*Mean (SD)*	*t*	*p*	*Mean (SD)*	*t*	*p*
				WRT					
-4	.987 (.072)	1.044	.306	1.059 (.104)	1.782	.085	1.054 (.155)	1.528	.144
-2	.986 (.076)	1.054	.301	1.074 (.084)	1.364	.180	1.105 (.108)	4.189	.001**
0	.872 (.105)	6.863	.000**	1.146 (.106)	3.852	.000**	1.136 (.306)	1.931	.069
2	.992 (.120)	.347	.731	1.046 (.057)	1.130	.264	1.051 (.257)	.737	.474
4	.957 (.144)	1.547	.134	1.043 (.071)	1.108	.273	1.059 (.220)	.848	.405
				RWT					
-4	.976 (.124)	1.357	.181	1.028 (.105)	.991	.401	1.065 (.158)	1.841	.081
-2	1.002 (.145)	.118	.906	1.009 (.076)	.797	.430	1.041 (.125)	1.373	.189
0	.993 (.106)	.465	.644	1.033 (.069)	2.939	.006**	1.098 (.190)	2.305	.033*
2	1.015 (.072)	1.627	.109	1.029 (.084)	2.075	.045*	1.084 (.148)	2.824	.009**
4	1.005 (.074)	.422	.575	1.019 (.083)	1.128	.271	1.136 (.388)	1.564	.134

Table 5. The symmetry index

One sample T-test was used to explore differences between the symmetry index (SI) and 1: ** $p<0.01$, * $p<0.05$. SI's were calculated over one stride. So, stride -4 refers to the stride between heel contact of step-4 and heelcontact step-2, …

SI's were only reported from step-4 to step +4 as no significant differences were found among WS and RS. Thus, SI's of stride -8, -6, 6 and 8 reveal SI's that are not significantly different from 1.

4. Energetic fluctuations of the centre-of-mass (Fig. 6)

As can be seen in figure 6 (p. 93), there is a sudden transition from an out-of-phase organization (green arrow) of gravitational potential and kinetic energy of the centre-of-mass (COM) to an in-phase organization (red arrow) during the TS in the WRT. The opposite is observed during the TS of the RWT: a switch from in-phase to out-of-phase energy fluctuations of the COM.

DISCUSSION

Transition speed (2.16 and 2.19 m s^{-1}) was slightly higher than the transition speed observed in the studies of Li and Hamill (2002), Getchell and Whitall (2004) and Thorstensson and Roberthson (1987), though in the same speed range and comparable to other studies (Abernethy et al., 1995; Diedrich and Warren, 1995, 1998; Hanna et al., 2000; Mercier et al., 1995; Raynor et al., 2002; Segers et al., 2006)

1. Sudden event or Gradual process?

Kinematics of the actual realization of transition in a protocol with gradually changing speed has never been examined before, except by Abernethy et al. (1995) for the shank segment. Therefore, this study allowed interpreting the realization of transition for the first time. To acquire a clear view on the whole body coordination, stickfigures were made of the TS in WRT and RWT and of a WS and a RS (Fig. 5).

The primary goal of the present study was to reveal whether transition is a sudden one step event or a process covering several steps during which the transition is completed to continue locomotion in a stable new gait pattern. In order to answer this question, one of the primary issues was to reveal significant differences between steps. Emphasis in the results-section was placed upon the differences between WS & TS and RS & TS because (as mentioned in Material and Methods, partim Statistics) only few differences were found among WS and RS. Graphical differences (as they can be observed in Figs. 2-5) were confirmed with statistics (Tables 2-4).

Based upon lower limb kinematics, one might say there was a sudden change from one gait to the other in the WRT as well as in RWT. However, simply concluding that transition was a one step event would be ignoring some of the essential differences that occur during the last swing before transition in the WRT and the first stance after transition in the RWT assisting in the realization of transition. For the WRT, it is remarkable that at the start of the TS the limb had an altered landing configuration already resembling the running configuration due to a preparation during swing of the last walking stride. In the RWT no different landing conditions were found for the TS and adaptations to the walking configuration mainly occur during stance of the TS, but transition was only completed after stride+2 by a reorientation of the trunk.

Our first two hypotheses have been confirmed. Transition (WRT and RWT) was mainly realized during one discrete step (Fig. 5, Tables 2-4). However, there was a "pre"paration of the WRT during the last stride to facilitate transition by adapting the landing configuration and a "post"paration of the RWT in which the trunk configuration was only optimized during step+2.

How do these findings add to previous research indicating a transition process?

Li and Hamill (2002) found a decrease of the second peak of the vertical ground reaction force in the last step prior to WRT. They hypothesised that this could be due to a modification of the ground reaction force vector flattening the trajectory of the COM, thereby increasing forward velocity of the trunk. This reasoning can be confirmed by the present research as we find an increase of the anteversion of the trunk during the last walking stride (Fig. 4c).

Segers et al. (2006) described a pre-transition process in the WRT and a post-transition process in the RWT for the spatiotemporal factors, Opposed to the expected linear evolution of step length and step frequency, Segers et al. (2006) found a non-linear evolution of the spatiotemporal factors during this transition process consisting of approximately eight steps. Parallel to this study (Segers et al., 2006), in the present research WRT is also prepared and realized during the TS whereas RWT is only completed in the first WS. It is not clear why there is this discrepancy in the duration of the transition process. It remains puzzling that changes in spatio-temporal characteristics do not go hand in hand with changes in kinematics. One might reason that the summation of small but non significant adaptations in kinematics reinforced each other resulting in the unique change of the spatiotemporal factors. Further research is necessary to seek this out.

2. Kinematic definition

To discern walking from running kinematically, the knee-angle is the pre-eminent variable. A more extended knee is inherent to the walking pattern whereas more knee flexion is typical in running. Besides this, there are two other manners of distincting both forms of locomotion: the spatiotemporal definition [double stance = walking (duty factor > 0.5); flight phase = running (duty factor < 0.5)] and the energetic definition (potential and kinetic energy out-of phase in walking and in phase in running) (Alexander, 2004; Farley and Ferris, 1998).

Are the spatiotemporal, dynamical and the kinematic definitions tuned to each other? In other words, does a flight phase inherently cause the system to convert to in-phase fluctuations of kinetic and potential energy and simultaneously flexing the stance limb?

The present results indicated that the three ways of defining indicate the same transition step when gradually accelerating/decelerating across the transition (Fig. 5). In the WRT, the first step with a flight phase indeed showed more flexion of the knee. The COM gave an indication of changing from the inverted pendulum (highest point at midstance) to the spring-mass (lowest point at midstance) during the TS.

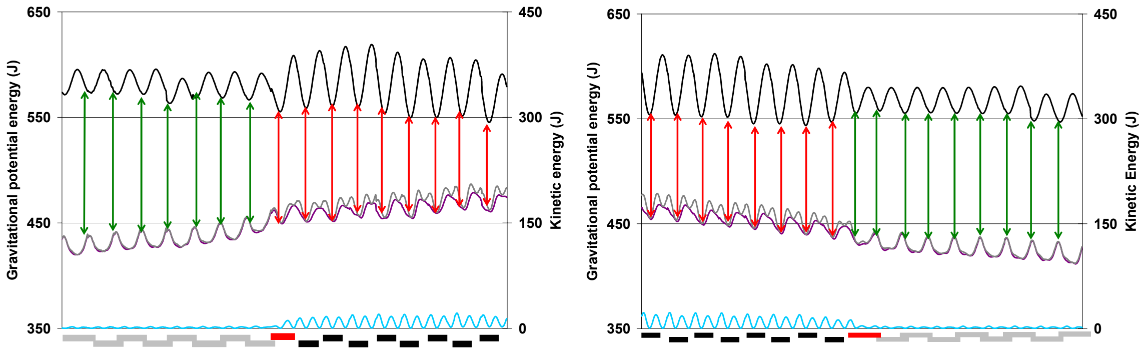

Figure 6. Energy exchange of the centre-of-mass

Green arrows represent an out-of-phase exchange between gravitational potential energy and kinetic energy in the (a) WRT and (b) RWT. Red arrows represent in-phase fluctuations of the latter two. On the X-axis contact with the ground is indicated by rectangles (grey: WS, red: TS, black: RS).

— Epot = Gravitational potential energy
— EkinX = Kinetic energy in X (anterior-posterior) direction
— EkinZ = Kinetic energy in Z (upward) direction
— EkinTOT = EkinX+EkinZ

In the RWT on the other hand using the kinematic definition of the TS was not so obvious. At heel contact (of all examined strides), there is no difference in knee-angle between walking and running (Fig. 3d). During stance the knee joint flexed in running, whereas its position did not change during walking. The knee during TS was an intermediate and hard to distinguish from the previous RS (Figs. 3d and 5). The COM reached its highest point at midstance during the TS despite the "running start" of the TS.

Energy fluctuations of the COM define walking and running. Therefore, we calculated horizontal and vertical kinetic energy and the gravitational potential energy of the COM. As can be seen in figure 6, there was a sudden change from potential and kinetic energy fluctuating out-of-phase to in-phase in the WRT and vice versa in the RWT. Therefore we could conclude that “Walking is Walking & Running is Running”, even in proximity of transition. Or in other words: the definitions of walking and running indicated the exact same step as the transition step.

3. Interlimb coordination

The last part of this discussion shall be devoted to the interlimb coordination of transition. Walking and running are two symmetrical gait patterns (Fig. 1a) (De Cock et al., 2005; Getchell and Whitall, 2004; Sadeghi et al., 2000). The transition stride, on the other hand, is characterized by asymmetry because within one stride one leg is walking and the other is running (Fig. 1b: Segers et al., 2006). Is this asymmetry a fourth way of detecting the TS?

In the WRT, symmetry was present in all WS and RS except for the positioning of the thigh during the last WS (Table 5). This was in agreement with the preparation of the system for transition to the running gait. The TS was characterized by a large amount of asymmetry in foot and shank. No asymmetry, however, was found for the most proximal thigh-segment. This means that the WRT was asymmetrical on a more distal level during the actual transition after proximal preparation of the system (thigh).

In the RWT on the other hand the distal segment (foot) showed no asymmetry at all, whereas shank and thigh showed asymmetry during transition step and the first walking step. This asymmetry reinforced the ‘post’paration of the RWT.

One could say that asymmetry as indicated in the coordination pattern of the TS was a fourth way of defining the transition between walking and running. When asymmetry disappeared, transition was completed in both WRT and RWT.

Despite the fact that there was no hysteresis in the strict sense (WRT- and RWT-speed did not differ), functional hysteresis, by which the different realization of WRT and RWT is indicated, was present (Segers et al., 2006). The transition from one mode of locomotion to another took place in the walking steps close to transition as well in the WRT (before transition point) as in the RWT (after transition point). This finding in combination with earlier findings in spatiotemporal characteristics indicate that the running steps are more attached to a unique step frequency/step length ratio and kinematic pattern, which could be related to the strength of the running attractor.

4. Conclusion

Human gait transitions are mainly realized in one transition step indicating a discontinuity. However, regardless of this transition step, a transition process covering several steps is present to reorganize the system and continue in a new stable gait pattern. In the WRT transition is prepared during swing of the last walking stride and terminated after the TS. In the RWT, on the other hand, no preparation is observed but transition is completed after reorientating the trunk during the first walking stride. The TS is characterized by a unique interlimb asymmetry, in contrast to the symmetry of WS and RS. Furthermore, kinematic, energetic and spatiotemporal definitions of the transition point were found to correspond in WRT and RWT.

ACKNOWLEDGMENTS

This research was supported by BOF–RUG B/03796/01– IV1. The authors acknowledge Ing. P. Van Cleven and Ing. D. Spiessens for data collection and technical support and Lic. K. De Smet and Lic. P. Malcolm for their professional advice. The authors also thank Prof. Dr. D. Adriaens (Ghent University, department of Vertebrate Morphology & Zoology Museum) for the use of the JVC high-speed camera.

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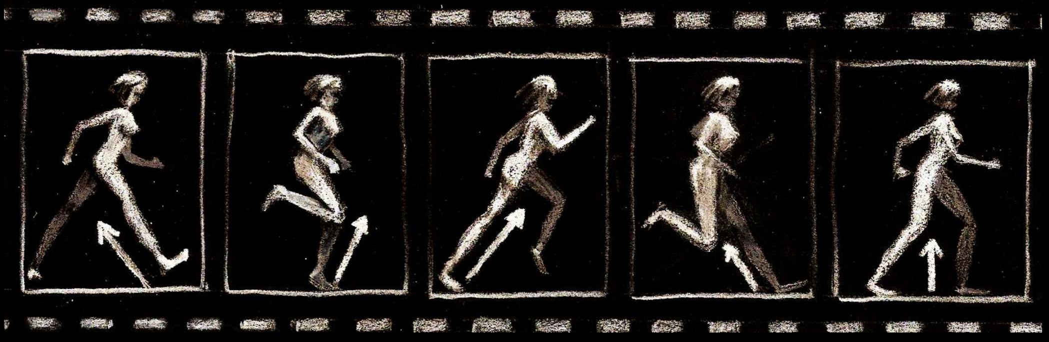
Chapter 4

Dynamics of the body centre of mass during actual acceleration across transition speed



ABSTRACT

Judging whole body dynamics, walking and running in humans clearly differ. When walking, potential and kinetic energy fluctuate out-of-phase and energy is partially recovered in a pendulum-like fashion. In contrast, running involves in-phase fluctuations of the mechanical energy components of the body centre of mass, allowing elastic energy recovery. We show that, when constantly accelerating across the transition speed, humans make the switch from walking to running abruptly in one single step. In this step, active mechanical energy input triples the normal step-by-step energy increment needed to power the imposed constant acceleration. This extra energy is needed to launch the body into the flight phase of the first running step and to bring the trunk in its more inclined orientation during running. Locomotor cycles immediately proceed with the typical in-phase fluctuations of kinetic and potential energy. As a result, the pendular energy transfer drops in one step from 43% to 5%. Kinematically, the transition step is achieved by landing with the knee and hip significantly more flexed compared to the previous walking steps. Flexion in these joints continues during the first half of stance, thus bringing the centre of mass to its deepest position halfway through stance phase to allow for the necessary extension to initiate the running gait. From this point of view, the altered landing conditions seem to constitute the actual transition.

Keywords: Biomechanics, Walking, Running, Transition, Centre-of-mass

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Submitted to 'The Journal of Experimental Biology'

INTRODUCTION

When walking faster and faster, humans will spontaneously start running. Generally, both gaits are distinguished from each other on the basis of the difference in dynamics of the body's centre of mass (Alexander, 2003; Cavagna et al., 1977; Farley and Ferris, 1998; Mochon and McMahon, 1980; Srinivasan and Ruina, 2006; Willems et al., 1995). Walking is characterized by out-of-phase oscillations of kinetic and gravitational potential energy of the body centre of mass (COM), whereas in running these mechanical energy components fluctuate in-phase, in literature often referred to as the inverted pendulum and spring-mass paradigms, respectively (Blickhan, 1989; Blickhan and Full, 1987; Cavagna et al., 1977; Mc Mahon and Cheng, 1990; Mochon and Mc Mahon, 1980; see also review Farley and Ferris, 1998). Recently, Geyer and co-workers developed a spring-mass model for walking which showed that limb compliance plays a functional role not only in bouncing gaits but also in the vaulting walk (Geyer, 2005; Geyer et al., in press).

Next to this dynamic discrimination, a more operational definition, based on spatio-temporal characteristics is often used to discern walking from running in human gait analysis: duty factors (the fraction of the stride time a particular limb is in stance) above 0.5 are referred to as walking; duty factors (DF) below 0.5 characterize running gaits (used for instance in Aerts et al, 2000; Ahn et al, 2004; Alexander, 1989 and 2004; Bramble and Lieberman, 2004; Donelan and Kram, 1997 and 2000; Farley and Ferris, 1998; Gatesy, 1999; Grieve and Gear, 1966; Minetti, 1998; Minetti and Alexander, 1997; Nilsson and Thorstensson, 1987; Rubenson, 2004; Segers et al., 2006; Van Coppenolle and Aerts, 2004; Verstappen and Aerts, 2000; Zatsiorsky et al., 1994). When this spatio-temporal definition is applied to the natural gaits of humans, the distinction between walking and running is very clear and strict (but see below). A double stance phase (DF > 0.5; walking) is either present or not and the transition between both modes of locomotion when defined on the spatio-temporal basis evidently occurs within one step (Segers et al., 2006).

From animals it is known that transition speeds defined on the basis of the above criteria might differ. Some birds, crabs, primates and elephant, for instance, show dynamic running, while still walking spatio-temporally (DF > 0.5; e.g. Alexander and Jayes, 1978; Blickhan and Full, 1987; Gatesy, 1999; Gatesy and Biewener, 1991; Hutchinson et al., 2003; Kimura, 1996; Muir et al., 1996; Schmitt, 1999 and 2003). This is known as ‘grounded running’ (Rubenson, 2004) or Groucho running (McMahon et al., 1987). In humans, it is still an open question whether gait discrimination according both definitions concur or not.

Moreover, to date (and despites the common use of COM-dynamics to discern walking from running), nothing is known about how precisely the behaviour of the COM changes at transition. Do the COM-dynamics *gradually shift* from the walking to the running state? In other words: does the characteristic vaulting pattern of the COM (inverted pendulum) flattens step by step when approaching the transition speed, to pass smoothly into the (spring-like) sagging of the stance limb when running? Or, does a *transition in a more mathematical sense* exist, being characterized by a sudden and clear discontinuity in mechanical behaviour?

Although many studies discuss aspects of the transition between walking and running in humans, most are based on the analyses of locomotion at steady speeds (Daniels and Newell, 2003; Getchell and Whitall, 2004; Hreljac, 1993a/b,1995a/b; Hreljac et al., 2001;Mercier et al., 1994; Minetti et al., 1994; Neptune and Sasaki, 2005; Nilsson et al., 1985; Nilsson and Thorstensson, 1989; Prilutsky and Gregor, 2001; Raynor et al., 2002; Sasaki and Neptune, 2006). Only few report on what happens when actually accelerating across the transition between walking and running. (Diedrich and Warren, 1995, 1998; Li 2000; Li and Hamill, 2002; Segers et al., 2006; Thorstensson and Robertson, 1987). Yet, knowledge gained from such conditions allows one to obtain insights into the manner in which COM-dynamics change through transition. In this way, the interplay between neuromuscular control and the physical characteristics of the human locomotor system (Farley and Ferris, 1998) as well as the level of self-organization in motor control (Aerts et al., 2000; Diedrich and Warren, 1995) can be addressed.

In order to fill this lacuna, the aim of the present paper is to provide answers to the next questions. How does COM-dynamics change during human locomotion when actually accelerating across the transitions speed? What are the dynamical and kinematical aspects behind the observed behaviour of the COM at transition? What is the relationship between the spatio-temporal and dynamical definitions of walking and running in humans?

METHODS

1. Subjects and set-up

To assess transition during constant acceleration we chose for studying overground rather than treadmill locomotion in order to exclude any potential artefact. Nine female subjects participated in the present study. The influence of anthropometry was minimized by selecting test persons within a limited height and mass range (1.69 ± 0.03 m; 64.89 ± 4.52 kg) (Getchell and Whitall, 2004; Hreljac 1995a). They were instructed to follow a constantly accelerating running light (0.15 m s^{-2}) along a 50m long running track. The accuracy by which they did was visually judged by three experienced researchers. After 35 meters along the track, 3D kinematics were recorded in a volume sufficiently large (± 7 m) to cover 6 to 7 successive steps (240 HZ using 8 infrared cameras (Pro Reflex) and Qualisys software). Trials were selected for further analysis when the acceleration was scored as constant by the three observers and when the transition occurred within the volume captured by the camera system. Steps (from one heel contact to the next) were labelled in the following way: *step 0* = first step without double support phase = transition step; *step –n* = *n*th step before *step 0*; *step n* = *n*th step after *step 0*.

Anatomical reflective markers were placed according to McClay and Manal (1999) on the greater trochanter, the medial and lateral femoral condyles, the medial and lateral malleolus, the medial and lateral part of the calcaneus, the head of the first and fifth metatarsals, the anterior superior iliac spine, the top of the acromion, the medial and lateral epicondyle of the humerus and the styloid processes of radius and ulna. The tracking markers consisted of rigid plates secured to the thigh and the shank and of markers on the calcaneus, on top of the foot arch, on the os sacrum and on the 7th cervical vertebra. Three markers were also used to track the movements of the upper and lower arm. Following calibration (recording while standing), subjects were familiarized with the test protocol. Raw displacement data were filtered using a Butterworth low pass filter at 18Hz.

2. COM-position and validation

A 11-segment model (forearms, upper arms, head+trunk, thighs, shanks, feet) was used to calculate the position of the COM (Visual 3D v3.19.0, USA) for the 6 to 7 steps captured by the camera system. To validate these calculations, a 2m AMTI force plate was built into the running track in order to obtain ground reaction forces of one (occasionally two) of the video-captured steps. The track was covered with uniform grey carpet in order to avoid aiming for the force plate. Thus, ground reaction forces were randomly obtained within the range of step -3 (i.e. last three walking steps before transition) to step +3 (i.e. first three running steps after transition), depending upon where precisely in the covered 3D-volume transition occurred.

For 20 steps, COM displacements were calculated from the force recordings (double numerical integration of accelerations deduced from the forces; cf. Eames et al., 1999) and compared with the associated COM displacements as obtained from the kinematic recordings (example in Fig. 1). Average measures of intra-class correlation coefficients were calculated and resulted in values varying between 0.920 and 0.987 ($p<0.01$). This, together with the fact that COM displacements as obtained from both methods fluctuate about the same mean ($p=.408$), indicated that kinematic measures were highly reliable. Therefore the method presently used to obtain the instantaneous horizontal and vertical position of the COM for seven successive over-ground accelerating steps, including the transition between walking and running is supported. First and second derivatives of these positions against time yielded velocities (horizontal: v_x, vertical: v_z) and accelerations (horizontal: a_x, vertical: a_z), respectively that were filtered using a Butterworth Low Pass filter at 18Hz.

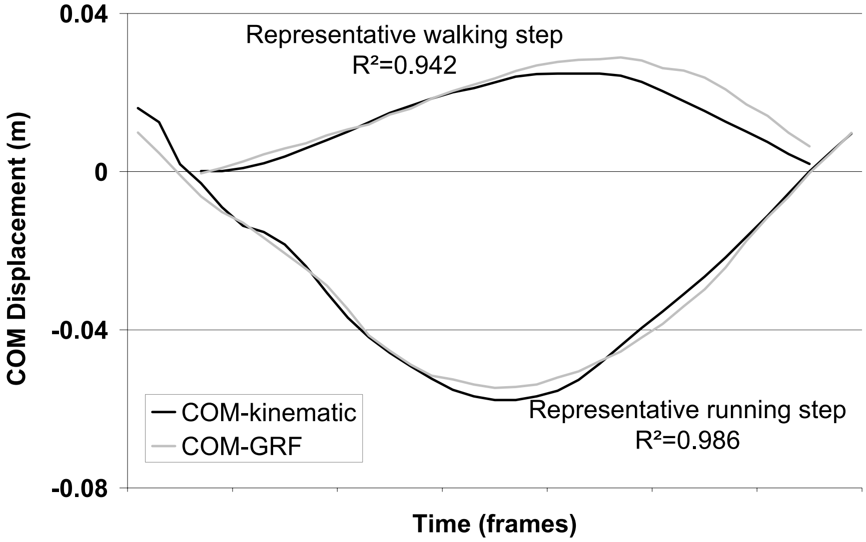

Figure 1. Comparison of the vertical displacement of the COM by means of ground reaction forces (GRF) and kinematically

One representative walking and one running step in the present protocol are shown. This comparison is made for available steps (at least one for each subject).

3. Energy and Power

Gravitational potential energy [Epot = mgh_i; with m the mass of the subject, g the gravitational constant (9.81m s^{-2}), h_i the instantaneous COM-height] and kinetic energy due to horizontal and vertical velocity (Ekin = $mv_x^2/2$ and $mv_z^2/2$, respectively) fluctuations of the COM were determined. Results were normalized over subjects and trials (cf. Fig.2) by expressing Epot as a fraction of mgh_r (with h_r the height of the COM in resting position) and Ekin as a fraction of $mv_{trans}^2/2$ (with v_{trans}= the trial specific horizontal speed at which transition occurred). Instantaneous power profiles for the COM were calculated [$P_x = ma_xv_x$; $P_z = m(g + a_z)v_z$; $P_{ext} = P_x + P_z$]. To estimate pendular energy transfer (R_{step} cf. Cavagna et al., 2002), the positive work done on the COM in horizontal direction (^+W_x), in vertical direction (^+W_z) and the positive external work in the sagittal plane ($^+W_{ext}$) were calculated by integrating the positive phases of the associated power profiles (P_x, P_z, P_{ext}, respectively) during single stance. The fraction of mechanical energy exchange is given by: $(^+W_x + {}^+W_z - {}^+W_{ext})/(^+W_x + {}^+W_z)$, yielding in essence the calculation method used in Heglund et al. (1982).

4. Regressions and statistical comparisons

The kinetic energy regressions against time were calculated for walking and running steps separately. As kinetic energy is a function of the velocity squared, an accelerated movement yields a non-linear relationship between Ekin and time, by definition. However, because of the limited velocity range considered, exponential and linear regressions are virtually identical (very similar R^2-values). Therefore, linear regressions were used for simplicity reasons: their slopes represent the average power necessary to accelerate over the involved velocity ranges.

A repeated measures ANOVA with post hoc Bonferroni tests was used to examine differences in R_{step} and kinematic variables between the 7 successive steps and in slopes and intercepts between walking, transition and running.

RESULTS

1. General

Based on the kinematics of the body centre of mass (COM), the forward speed at the heel contact initiating *step 0* equals 2.17 m s^{-1} (± 0.02 m s^{-1}; see also table 1). This is presently considered the walk-to-run transition (WRT) speed. Measured over the time intervals coinciding with *step -3* to *step -1*, as well as *step 1* to *step 3,* the acceleration of the COM equals 0.15 m s^{-2} (± 0.02 m s^{-2} and 0.03 m s^{-2}, respectively). This is identical to the imposed acceleration of the running light (see Materials & Methods). Over the course of *step 0*, however, the measured velocity increase of the COM accords to an acceleration of 0.23 m s^{-2} (± 0.03 m s^{-2}). This is reflected in a tripling of the net work and mean step power required for *step 0*, when compared to that required for the preceding walking, respectively succeeding running, steps (see below). Table 1 presents the step durations and velocities at initial contact for all examined steps (*-3* to *3*).

		Walking steps			Transition step	Running steps		
Step		*-3*	*-2*	*-1*	*0*	*1*	*2*	*3*
Velocity (m s^{-1})	X	1.95	2.03	2.10	2.17	2.31	2.38	2.45
	SD	0.15	0.14	0.16	0.19	0.19	0.22	0.21
Step duration (s)	X	0.48	0.48	0.46	0.47	0.41	0.41	0.40
	SD	0.02	0.02	0.02	0.05	0.03	0.04	0.04

Table 1. Velocity and step duration
X = mean, SD = standard deviation.

2. Kinetic and potential energy fluctuations

Figure 2a shows that fluctuations in kinetic and gravitational potential energy of the COM abruptly change from an out-of-phase (red arrows) to an in-phase (blue arrows) pattern. As a result, the pendular energy transfer drops in one step from 43% to 5 % (Fig. 2a). Potential energy (Fig. 2a) naturally fluctuates about mgh_r (relative=1, purple line in Fig. 2a), but amplitudes double when subjects start running. This is because at *step 0* the COM keeps lowering when leaving the vaulting pattern of the previous walking step (*step –1*; Fig. 2a).

Figure 2b presents linear regression of total kinetic energy against time for both walking (*step -3* to *step -1*) and running (*step +1* to *step +3*), separately. Slopes equal 22.37 ± 4.86 W and 23.53 ± 9.45 W and are a measure for the average power input needed to accelerate in the speed range covered during the last three walking steps and the first three running, respectively. As test persons followed a constantly accelerating running light, these slopes are statistically indifferent (p=.398). The intercepts, however, do differ significantly ($p<0.01$), representing a definite energy jump during *step 0* (the red arrow in Fig. 2b).

This means that at transition (*step 0*), active mechanical energy input (= 33.86 ± 8.70 J) triples the step-by-step energy increment needed to power the constant acceleration of progression at the transition speed (= 9.66 ± 1.09 J: the energy solely required to follow the accelerating running light during *step 0*). Apart from the latter component for overall acceleration, being approximately one third of the energy jump, another third (= 9.99 ± 1.99 J) of the energy input at *step 0* is required to increase the average kinetic energy from the walking to the running level (red arrow in Fig. 2c). The work for this extra kinetic energy is delivered during the second half of stance of *step 0* to accelerate the COM upwards in order to initiate the first small flight phase (Fig. 2c). The remaining third of the kinetic energy jump in *step 0* relates to *a short-lasting* increase in forward velocity of the COM, coming on top of the expected step by step velocity increase as a result of the overall acceleration. This is because the HAT-segment (head-arms-trunk) rotates further forward during stance of *step 0* compared to the preceding walking steps (*step -3 to step -1*) (Fig. 3b; i.e. increased range of motion). This results in a significantly larger forward displacement (hence forward velocity) of the COM during that step ($\Delta v = 0.06 \pm 0.03$ m s^{-1}, resulting in an increase of 11.74 ± 4.00 J). In the subsequent running steps (*step +1 to step +3*) the angular range of motion of the HAT decreases again becoming similar in magnitude to that observed in walking, but oscillations now occur about a more inclined position. Due to the latter, the forward velocity increase observed in *step 0* (to bring the trunk in the running configuration) was not observed in the running steps. So the slopes of the regressions in kinetic energy due to horizontal velocity of walking and running steps did not differ (Fig. 2b).

3. Kinematical realization of the transition step

Figure 3a illustrates how the switch from walking to running is realized kinematically. In *step 0*, the foot placement occurs more in front of the hip, with significantly more plantar, hip and knee flexion ($p<0.05$) compared to the landing configurations in the previous walking steps (step -3 to step -1). This altered landing condition is prepared only lately in the preceding swing phase (last 15% of swing phase duration, Fig. 3c). During the subsequent stance, hip knee and ankle go first further in deeper flexion lowering the COM (instead of the typical upwards vaulting motion observed in the previous walking steps). This allows for more powerful leg extension during the second part of stance, sufficient to propel the body in its first flight phase. As a result, the change in dynamics (from out-of-phase to in phase fluctuations) and the transition according to the kinematical definition (duty factor < 0.5 (Alexander, 1989; Farley and Ferris, 1998; Segers et al., 2006) occur in the same step.

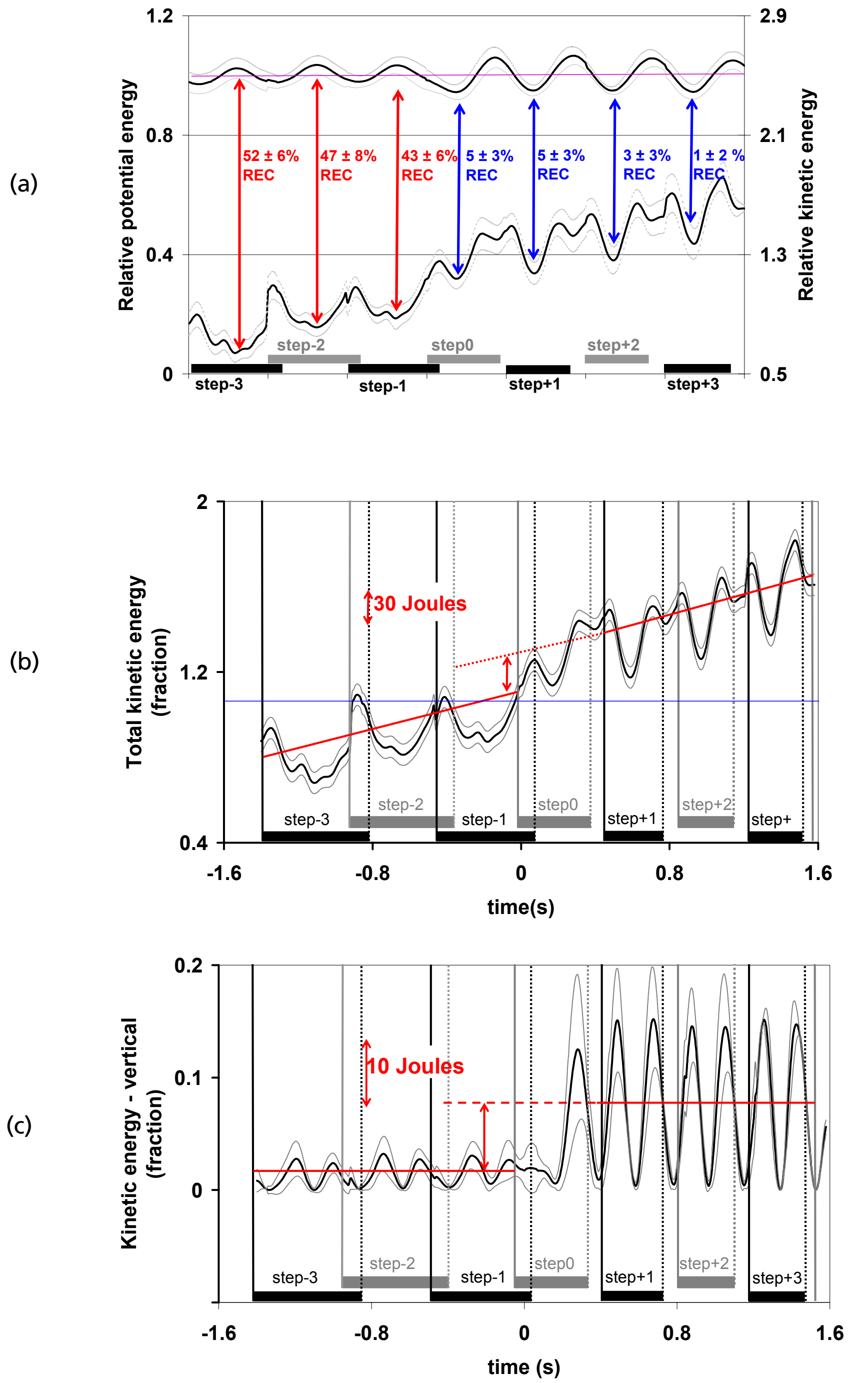

Figure 2. Energy fluctuations of the COM

Figure 2a represents the out-of-phase (walking-red arrows) and in-phase oscillations (running-blue arrows) of kinetic energy and gravitational potential energy of the COM on a normalized time-basis with an indication of the efficiency of energy exchange (%REC = percentage recovery pendulum). Figure 2b is a graph of the total kinetic energy (fraction of total kinetic energy at heel contact of the transition step indicated by grey line) and the linear regressions for walking and running steps. Figure 2c represents the kinetic energy due to vertical velocity of the COM (fraction of total forward kinetic energy at transition)with the horizontal regressions for walking and running steps.

Average of the average of all trials (n= 3-5) of each subject (n=9) is represented with the black line. Grey lines indicate standard deviation between subjects. Contact with the ground (X-axis) is represented by grey and black bars.

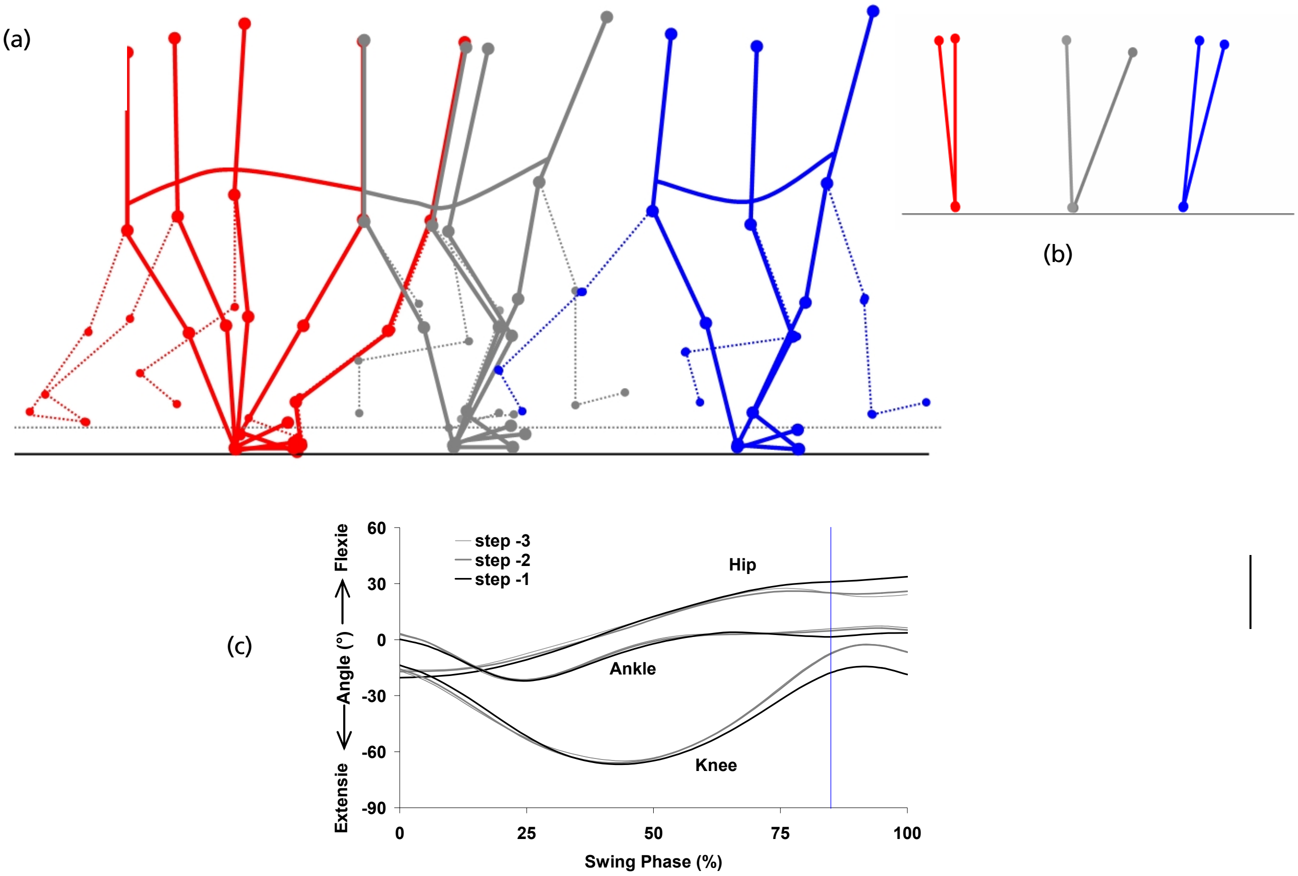

Figure 3. Kinematics of the transition

Figure 3a represents the average kinematics of the last walking step, the transition step and the first running step. The red line represents the last walking step, the grey line the transition step and the blue line the first running step. Stick figures were created at specific key events of each step, being heel contact, opposite toe-off (in case of WS and TS), midstance, oppositie heel contact (in case of WS) and toe-off. In figure 3b, the ROM of the trunk is represented.

Figure 3c represents hip, knee and ankle angle during swing in the last walking steps. Step -3 is drawn with a light grey line, step -2 a grey line and step -1 a black line. Negative sign stands for flexion (ankle – dorsiflexion), a positive sign for extension (ankle – plantar flexion). The vertical blue line indicates the beginning of the final 15% of the swing phase.

4. Power of the COM

Instantaneous COM power profiles presented in figure 4 confirm the above conclusions. For running steps, negative COM power early in stance represents energy extracted from the system, either dissipated as heat or temporarily stored as elastic energy in tendinous structures. In the latter case, this energy can be recovered during the second part of stance when energy is added to the system again (positive COM power). For *step 0*, however, negative COM power levels during the first part of stance remains very small, both in fore-aft (Fig. 4a) and vertical direction (Fig. 4b).

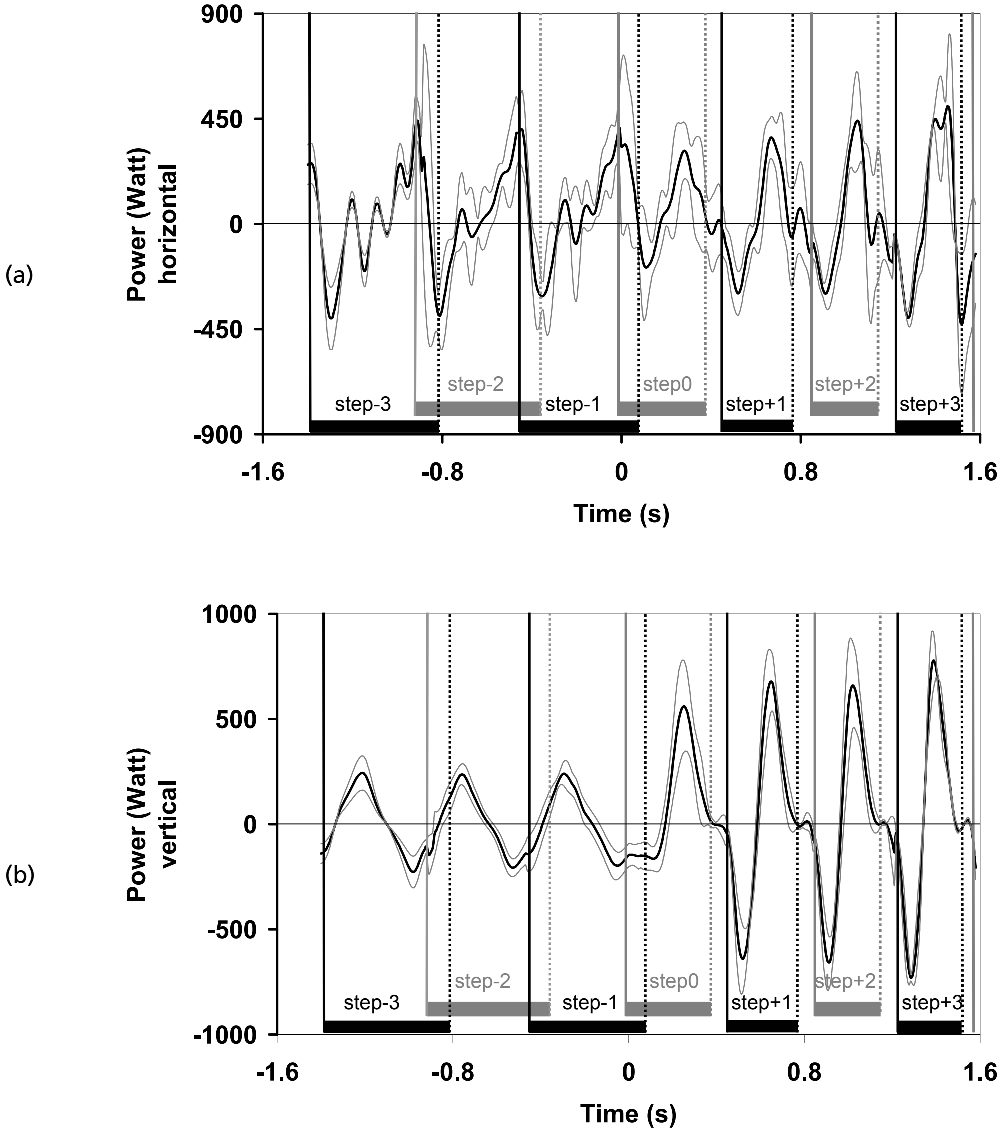

Figure 4. Power of the COM

Figure 4 represents average power fluctuations of the COM (a) horizontal and (b) vertical. Average of the average of all trials (n= 3-5) of each subject (n=9) is represented with the black line. Grey lines indicate standard deviation between subjects. Contact with the ground (X-axis) is represented by grey and black bars.

DISCUSSION

Above, we provide for the first time evidence that the transition between walking and running emerges as an abrupt change in the dynamics of the system. Furthermore, this transition is initiated just prior to foot placement of *step 0*. At this stage, it is unclear whether this ultimate adaptation of the swing phase is controlled or whether it reflects the intrinsic dynamics of the system. Similarly it remains an open question whether the deeper limb flexion in the first half of stance of *step 0* is actively controlled or whether it is just the result of the altered mechanical conditions at landing of step *0*. Regardless, it seems plausible that the deeper flexion and associated extensor lengthening trigger a simple reflex loop which initiates the increased extensor activity that generates the observed energy jump. The latter aspects need further research as it is impossible to speculate about the existence and the exact timing of this preparation without recording muscle activity.

During *step 0* negative COM power levels remain small. Consequently, the subsequent positive COM power peak must be delivered to a large extent by concentric muscle activity. Assuming 100% elastic storage and recovery of the negative COM power, still 68% ± 14% of the observed energy jump at transition (23.02 J) must be generated in this way. Given the observed kinematics (Fig. 3a-b), this is probably at the expense of the large extensor muscle groups of the knee and ankle of the stance limb.

Obviously the sudden shift in average position of the trunk resulting in the short lasting forward velocity increase of the COM (see above) also requires work to be delivered to a large extent by muscles. Simple modelling of the forward rotation of the HAT during stance of *step 0* as a result of the moment induced by gravity only (in practice: double integration of the angular equation of motion with gravity as the sole input) results in a rotation of 1.33°, which is merely a fraction of the observed displacement of 8.53 ± 0.94°. Therefore, active input from the muscles flexing the hip is also required for the forward movement of the trunk during *step 0*. Clearly, the latter are capable of delivering the necessary power as in other tasks the requirements prove to be much higher [i.e in countermovement jumping (Vanrenterghem et al., 2004)].

How does these findings compare to quasi static approaches in which steady state locomotion at different speeds is examined? Lee and Farley (1998) found that the trajectory of the COM is dramatically different between walking and running at the transition speed. At midstance the COM reaches its highest point during walking and its lowest point during running. In the present research these findings were confirmed as already during the transition *step 0* the COM had already reached it lowest point at mid-stance. Moreover, at heel contact of *step 0* even the stance-limb touchdown angle was adapted which is indicated by more flexion of knee and hip. According to Lee and Farley (1998) this is one of the essential differences leading to the different dynamics of walking and running. Comparison with other studies is difficult as as they have not closely examined the COM.

Recently, a published abstract by Lipfert et al. (2006) reports on subjects walking on a treadmill at a constant speed near the transition speed. Test persons performed the WRT on an acoustic signal, without changing however the overall locomotor speed (i.e. the belt speed). These authors found a difference in leg compliance (more knee flexion) and steeper angle of attack of the lower leg during *step 0*. Despite, the differences in the experimental protocols (constant velocity, conditional transition *versus* constant acceleration, spontaneous transition), these findings are in agreement with our conclusions.

As mentioned in the introduction very few papers deal with aspects of transition during actual acceleration. The WRT-speed in the present study is comparable (2.17 m s^{-1}) to these studies examining acceleration across transition speed on a treadmill (Diederich and Warren, 1995, 1998; Li 2000; Li and Hamill, 2002; Segers et al., 2006; Thorstenson and Robertson, 1987). In contrary to recent findings by Li and Hamill (ground reaction forces, 2002) and Segers et al. (spatiotemporal factors, 2006) WRT is only initiated shortly before landing of the transition step WRT and is completed during the course of the transition step. Furthermore, the methodological issue of the treadmill might be a factor not to be neglected. To explore the latter, further research in the transition phenomenon should examine kinematics and the behaviour of the COM in an accelerated protocol on a treadmill to explore differences and similarities with the present research.

ACKNOWLEDGEMENTS

This research was supported by BOF–RUG B/03796/01– IV1. The authors acknowledge Ing. P. Van Cleven and Ing. D. Spiessens for data collection and technical support; Prof. Dr. M. Lake (John Morse University, Liverpool UK) for his professional and language advice and Karlien Abrams and Kevin Coens for their help in data processing.

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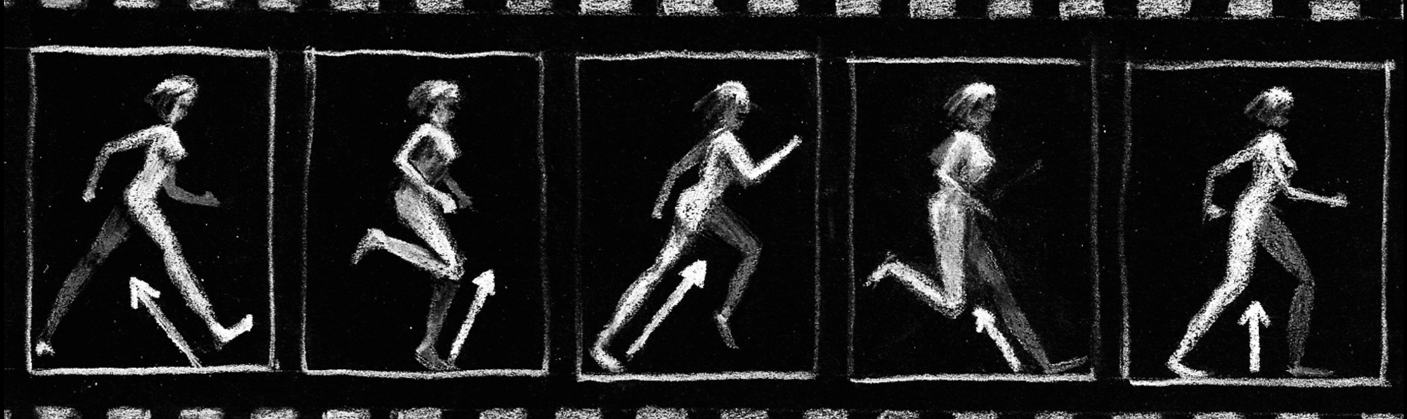
Chapter 5

External forces during actual acceleration across transition speed



ABSTRACT

The purpose of this study was to examine kinetics of the walk-to-run transition (WRT) and run-to-walk transition (RWT), when accelerating or decelerating across transition speed (a=0.17 m s^{-2}). Nine women performed gait transitions on a 50 meter long walkway. Vertical ground reaction forces (vGRF) and the centre-of-pressure (COP) were examined in the range from three steps before to three steps after transition in order to identify the possible occurrence of a transition process to facilitate the actual realization of transition.

The actual transition is merely realized in one step, during WRT and RWT. This transition step was characterized by an outlying vGRF's and COP trajectory (deviating from walking and running).

Despite this clear discontinuity, a transitional adaptation period (process) appeared in both transitions. In the WRT, transition was prepared and kinetic adaptations were found in the last step before transition. vGRF-pattern of step-1 are characterized by a smaller second peak and the COP has a faster forward displacement at the end of stance. RWT was pre- and 'post'pared and only completed during the first walking step after transition. The preparation existed of a smaller active peak in the GRF. Adaptations after transition were found in the larger first peak of the GRF during step+1. Thus, WRT and RWT are two different phenomena with different kinetic characteristics.

Keywords: Ground reaction forces, Centre-of-pressure, Gait Transition, Walking, Running, Biomechanics.

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Submitted to 'Research Quarterly for Sports and Exercise'

INTRODUCTION

In daily life, humans either walk or run and remain in that stable gait pattern when nothing changes or has to change (Alexander, 1989; Farley and Ferris, 1998; Minetti, 1994). However, when increasing or decreasing speed, humans change their way of moving after they crossed a certain limit. Humans do this without giving it any thought and without really testing the speed limits of walking and running (Hanna et al., 2000; Raynor et al., 2002; Thorstensson and Roberthson, 1987). Despite the growing interest in human gait transitions, there are still lots of questions about how humans change to another gait pattern at that specific speed although this knowledge may offer insight in the key factors that shape human locomotion (Farley and Ferris, 1998; Hanna et al., 2000; Li and Hamill, 2002; Raynor et al., 2002).

Neglecting air resistance, the ground reaction force (GRF) is the only external contact force during gait and reflects the dynamics of the locomotor system during stance. As such, the study of GRF could improve the comprehension of gait transitions. For instance, GRF are shown to be a potential factor triggering the trot to gallop gait transition in horses (Farley and Taylor, 1991). But, as most studies examined human gait transitions on a treadmill, kinetics of gait transitions are rarely analysed because an instrumented treadmill must be available (Li and Hamill, 2002; Raynor et al., 2002). Li and Hamill (2002) applied a protocol with gradually changing speed, whereas Raynor et al. (2002) used a protocol with stepwise changing constant speeds on the treadmill. Only Hreljac (1993; stepwise) and Segers et al. (submitted; gradual) studied transition overground.

In order to gain insight in the actual realisation of transition, a protocol with gradually changing speed is essential. Li and Hamill (2002) indicated a preparation with changes in the vertical GRF in the steps prior to the walk-to-run and run-to-walk transition (WRT respectively RWT) step. However, the transition step and the steps following transition were not examined. The question remains whether the reorganization to the new gait pattern is realized during the transition or only during the first steps after transition indicating the presence of a unique adaptation period, as shown previously in the spatiotemporal parameters and kinematics of gait transition (Segers et al., 2006).

Therefore, the aim of this study is to examine the evolution of GRF in the transition region (before, at and after the transition step, defined as the first step with a flight phase in WRT and first step with double stance in RWT) to explore the external forces when accelerating or decelerating across WRT- respectively RWT-speed overground.

Additionally, the displacement of the centre-of-pressure (COP) -instantaneous point of application of the ground reaction force (Miller, 1990)- will be measured as it will probably change in the transition region. This might give additional information about the transition phenomenon because plantar pressure measurements allow for the study of the foot-ground interaction (Alexander et al., 1990; Giaccomozzi et al., 2000; Titianova et al., 2004).

We hypothesize (1) that transition is mainly realized during the transition step with an intermediate pattern for both GRF and COP and (2) that, based upon the adaptation periods as described by Segers et al. (2006), unique transitional characteristics will be present in the last step(s) before WRT-step (‘pre’paration) and in the first step(s) after RWT-step (‘post’paration).

MATERIAL AND METHODS

1. Subjects

Nine female subjects participated in the present study. Influence of anthropometry was minimized by selecting test persons within a limited height and mass range (1.69 ± 0.03 m; 64.89 ± 4.52 kg) (Hreljac, 1995a; Getchell and Whitall, 2004). All subjects were free from injury and signed an informed consent prior to the start of the experiment. The local ethical committee approved the experiment.

2. Instrumentation

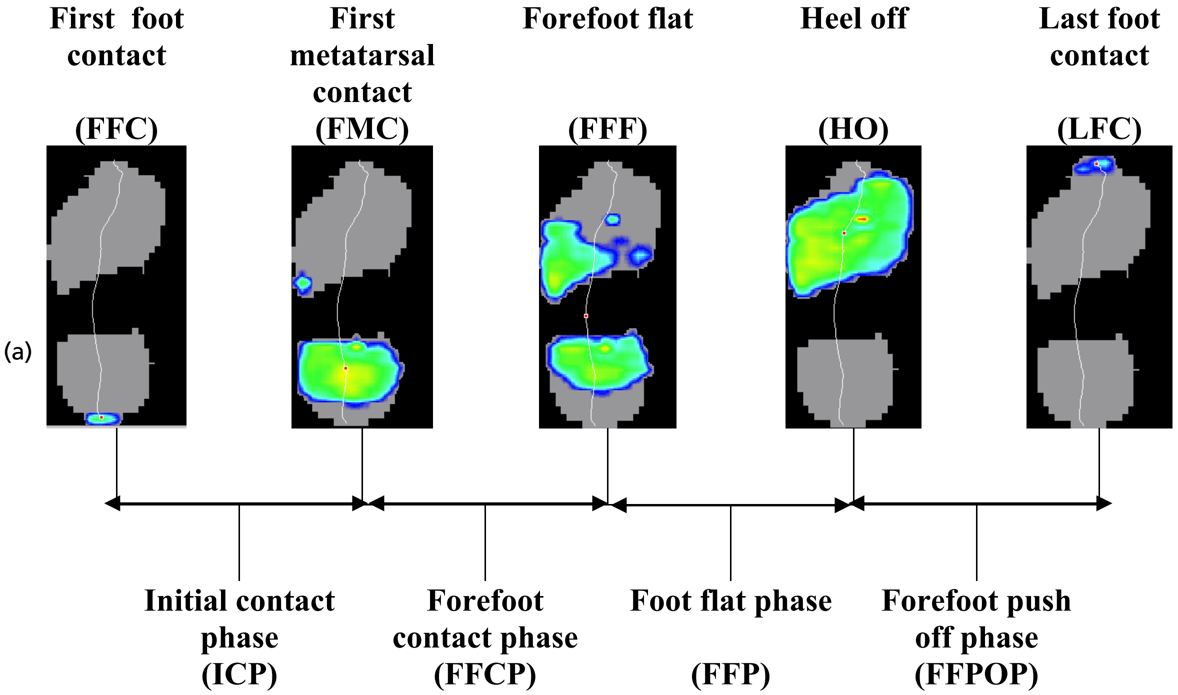
Vertical ground reaction forces (vGRF) were measured using an AMTI force plate (2 m x 0.4 m x 0.18 m) mounted in a 50 meter long running track after a distance of 35m. A plantar pressure measuring plate (FootScan ®, 2 m x 0.4 m x 0.02 m, with 16,384 resistive sensors, 120Hz, 2 sensors per cm²) was mounted on top of the force plate allowing for continuous calibration (sum of local forces = magnitude vGRF). vGRF and plantar pressure measurements were sampled simultaneously at 120 Hz. As the force plate was 2 meter long, usually more than one foot fall was detected on the plate. To split up vGRF, plantar pressure measurements were used. This technique, however, could not be applied for the horizontal GRF, which explains why they were not reported.

3. Protocol

Subjects were instructed to follow a constantly accelerating running light along the running track. The track was covered with rubcor (5 mm), in the same colour of the pressure plate to prevent the subjects from adjusting their running style while aiming at the plate. The accuracy by which they followed the light was visually judged by three experienced researchers. Trials were retained for further analysis when the subject's acceleration was scored as constant by the three observers and when the transition occurred in proximity of the plantar pressure measuring plate. In the retained trials average acceleration equalled 0.17 ± 0.05 m s^{-2}.

Using the vGRF, the transition step (*step 0*) was defined as the first step with a flight phase in the WRT and the first step with a double stance phase in the RWT. Steps before transition were given a negative sign, steps after transition a positive sign in and this for both protocols. Data were obtained within the range of step-3 to step+3 depending upon where precisely transition occurred. At least three recordings of vGRF and centre-of-pressure (COP) of each step were obtained. Initial contact with the plate was identified as the instant when at least three sensors are activated at a resultant force level of above 5N. An 8 bit A/D conversion was used and each sensor had a resolution of 0.5N, and maximum measuring range from 0 to 127 N. Stance phase duration was calculated using FootScan® software (RsScan International).

After normalizing GRF to body weight, first (Max1) and second (Max2) peak of the vGRF during the walking steps were determined (WS= walking steps during a transition protocol, W walking at preferred speed). For all running steps (RS= running steps during a transition protocol, R running at preferred speed) the impact peak (Max1) and the active peak (Max2) were retained.



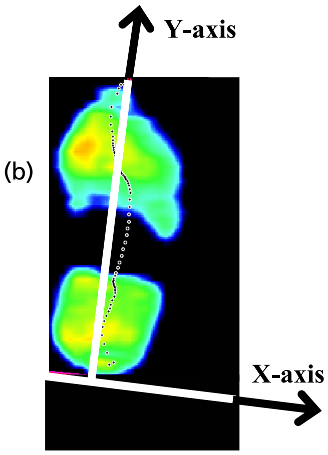


Figure 1. COP: functional phases & X- and Y-component

(a) Functional phases of the trajectory of the COP (De Cock et al., 2005; Willems et al., 2005)

(b) The X-component is positive when it is positioned medially of the heel-M2/3 axis. X-component and the Y-component were scaled to the shoe width and shoe length respectively.

For each plantar pressure trial, eight anatomical pressure areas were semi-automatically identified by the software. The automatically selected positions were checked by the experimenter and if necessary adjusted by the researcher (Footscan® software 7.0 Gait, RsScan international). These areas were defined as medial heel (H_M), lateral heel, metatarsals I – V and the hallux. As described by De Cock et al. (2005), for each trial five distinct instants of foot rollover were determined to divide the total foot contact in four phases: initial contact phase (ICP), forefoot contact phase

(FFCP), foot flat phase (FFP) and forefoot push off phase (FFPOP) (Fig. 1a).
The foot axis was automatically determined by the FootScan® software (adjusted when necessary) from the mid heel area to the second metatarsal (as described by Cavanagh et al., 1987). COP_x refers to the mediolateral displacement of the COP. If COP was positioned laterally of this axis, this was given a negative sign and medial a positive sign (Fig. 1b). COP_y refers to the anterior-posterior displacement of the COP along the foot axis. Afterwards, the COP_x and COP_y were scaled to shoe width and shoe length respectively (Fig. 1b). According to De Cock et al. (2005) forward displacement is dominant over medio-lateral displacement, which was confirmed in the present research (Figs. 1b, 2b and 3b). As the overall velocity was mainly determined by the forward velocity, we only took a closer look at this component.

4. Statistical analysis

SPSS for Windows (version 12.0) was used for statistical analysis. A repeated measures ANOVA with post-hoc Bonferroni tests was used to compare stance phase duration, Max1 and Max2 of vGRF and the duration of phases of the COP between 7 successive steps within WRT and RWT.

RESULTS

1. Stance phase duration

Differences between successive steps can be found in Table 1. Overall, last three WS have a longer duration than the first three RS during the WRT, and vice versa for the RWT. The TS is intermediate walking and running.

2. Vertical ground reaction forces (Figs. 2a and 3a, Table 1)

WRT

As can be seen in figure 2a, vGRF-pattern of WS differs from the RS during the WRT-protocol (Fig. 2a, Table 1). The TS has a single hump pattern with an intermediate character differing from WS and RS (Table 1). As can be seen in Table 1, the impact peak of step+1 is lower in comparison to the following RS.

RWT

Besides the impact peak at the beginning of stance, RS have a fast initial impact followed by an active peak. WS on the other hand are all characterized by a clear double hump pattern (Fig. 3a). The TS has a double hump GRF-pattern, although the depression between both maxima is not very pronounced (Fig. 3a). Among RS, only the active peak during step-1 is different from the other observed RS. Compared to the other WS, step +1 has a higher first peak and a lower second peak, leading to a clearly asymmetrical vGRF-pattern (Table 1).

3. Centre-of-pressure (Figs. 2b, 2c, 3b and 3c; Table 2)

WRT

An overall lateral to medial displacement of COP_x can be observed in all strides (Fig. 2b). At heel contact, COP_x is positioned more on the lateral side of the foot in the RS compared to WS (Fig. 2b, X-axis). Toe-off occurs more medial (more to the hallux) in the WS compared to the RS. COP_y is constantly moving forward (Fig. 2b, Y-axis). The combined trajectory of the COP during TS is intermediate WS and RS (Figs. 5a and 5b) evolving from the WS to the RS.

Forward velocity pattern of the COP during WS and W is characterized by an obvious triple peak velocity pattern (Fig. 2c). In R and RS this also appears but less obvious and with a clear dominance of the first peak. The TS has an outlying character typified by a first velocity peak, then followed a decrease of velocity of the COP (Fig. 2c).

Compared to RS, WS have a shorter ICP (except step+1), a shorter FFP and a longer FFPOP (Table 2).

RWT

Except for the TS, almost identical patterns can be observed during RWT when compared to the WRT (Figs. 3b and 3c). Therefore, only the TS shall be discussed. COP_x of the TS started in between WS and RS, then suddenly moved more to the medial side of the foot (Fig. 3b, X-axis). Forward velocity of the COP during TS has a triple peak pattern, already mimicking the pattern of the following WS (Fig. 3c).

Compared to the WS, RS have a longer FFCP (except step +1), a shorter FFP and a longer FFPOP (Table 2).

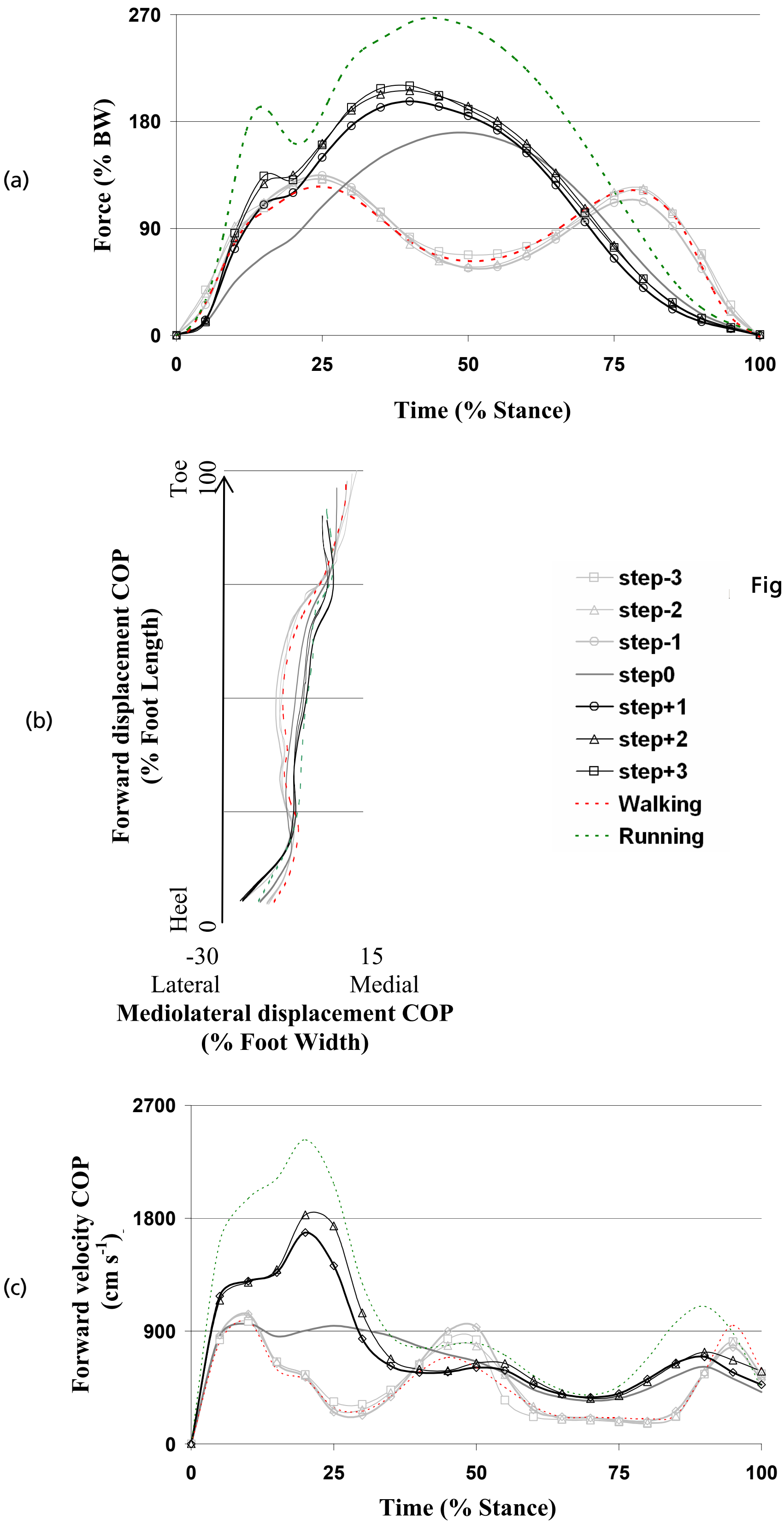


Figure 2. GRF and COP during WRT

(a) GRF normalized to body weight during WRT
(b) Displacement of the COP with mediolateral displacement normalized to foot width and forward displacement normalized to foot length
(c) Forward velocity of the COP

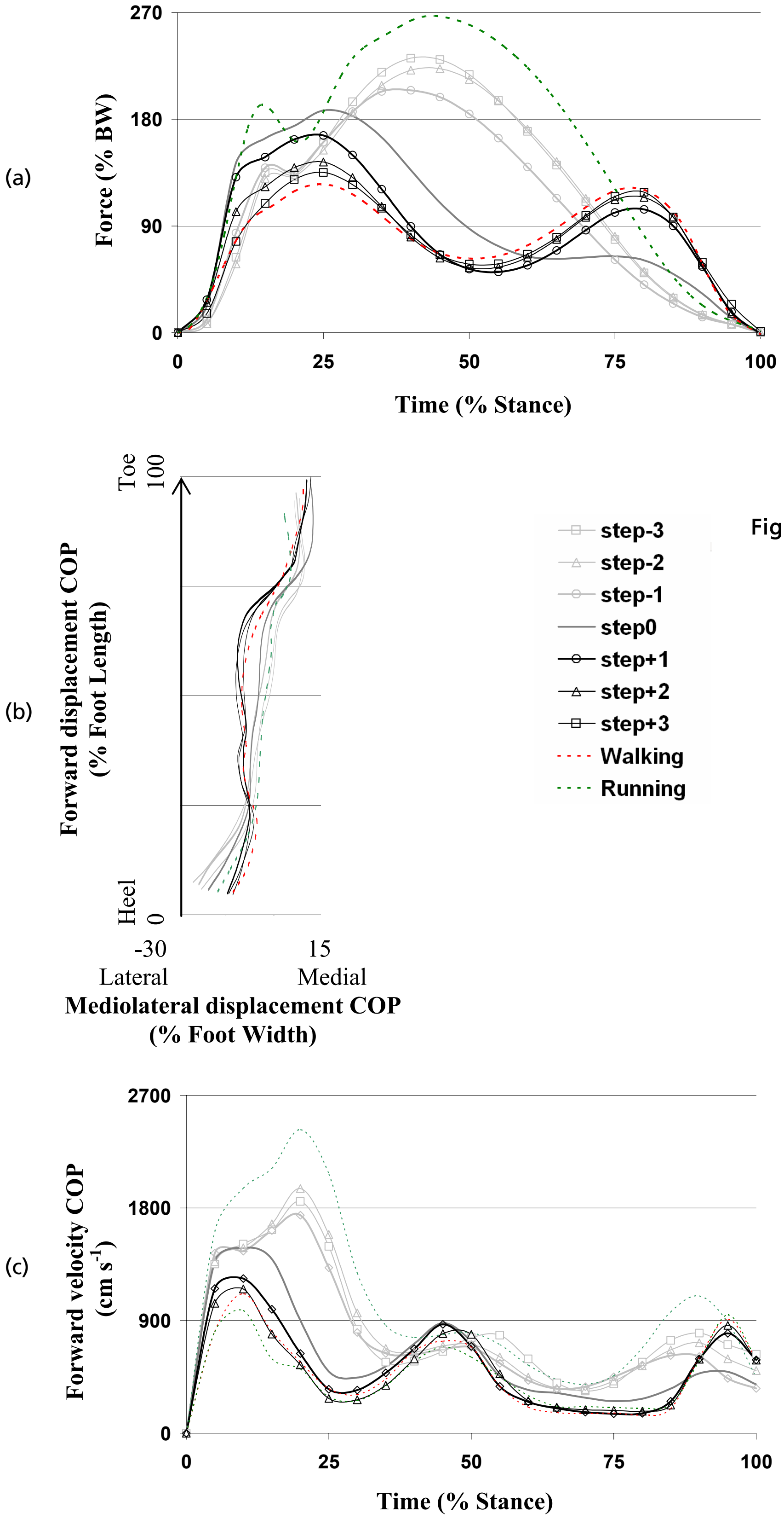


Figure 3. GRF and COP during RWT

(a) GRF normalized to body weight during WRT
(b) Displacement of the COP with mediolateral displacement normalized to foot width and forward displacement normalized to foot length
(c) Forward velocity of the COP

DISCUSSION

Our main hypotheses were (at least partially) confirmed. (1) Transition was mainly realized during the transition step with a deviating configuration for both COP and GRF. (2) In the WRT changes can be observed during step-1 in the GRF (lower second peak and through) and the impact peak of step+1 was lower compared to the following running steps. In the RWT, the active peak of step -1 was lower compared to previous running steps and step+1 showed a significantly different GRF-pattern.

Despite the larger active peak during running at preferred speed (associated to the difference in speed) the overall pattern of COP and GRF during walking steps (WS) and running steps (RS) in the transition protocol concur with the corresponding gait pattern (W, R).

1. A unique transitional behaviour

External forces and the COP during the transition stride of WRT and RWT have an outlying character with a deviant trajectory for GRF and COP. WRT- and RWT-step are not identical indicating functional differences between both transitions.

WRT

As can be seen in figure 2a, there is a sudden transition from a double hump pattern (walking) to a single hump (running) pattern with an intermediate single hump GRF pattern during the TS (no impact peak and lower active peak). The range of motion (ROM) of the COP_x was smaller during the TS because it was characterized by the more medial position of the COP_x at heel contact (similar to walking) and a more central toe-off (similar to running) clearly indicating the evolution from a walking to a running pattern. The total velocity of the COP during the TS is characterized by an approximately constant speed.

RWT

COP_x evolves from the more lateral position at heel contact of running to the more medial toe-off of walking, clearly indicating the realization of a run-to-walk transition. The trajectory of the COP during the TS is -after initial differences- functionally similar to the walking steps, which can be noticed in the velocity of the COP. The

GRF-pattern of the TS showed a double hump pattern although the second peak is not very pronounced. The inverted pendulum-like exchange of energy might not yet be optimized at that point. Temporal phasing of COP during TS does not differ due to the large standard-deviation.

2. Walking and running

Overall, WS and RS resemble the GRF- and COP-pattern of W respectively R. However, some differences were observed between successive steps within the transition protocols. Earlier research (Segers et al., 2006) showed a transition process for the spatio-temporal factors with the important difference that the present research is conducted overground in stead of using a treadmill.

WRT

Based upon previous findings of Li and Hamill (2002) and Segers et al. (2006), we hypothesized that a ‘pre’paration would be present in the WRT. In agreement with Li and Hamill (2002), the second GRF-peak, which is usually associated with the active push against the ground to move to the next step, was found to be lower during step -1 (last WS). This was accompanied by changes in the forward velocity of the COP at the end of stance (Figs. 2b and 2c). Li and Hamill (2002) linked the changes in second peak to a more forward lean of the trunk, which was recently observed by Segers et al. (submitted).

In contrast to the expectations, differences were also observed after the TS. The passive impact peak in step+1 (compared to the following RS) was lower, which can most likely be explained as a consequence of the unique transitional behaviour of the locomotor system generating only a short first flight phase (Segers et al., 2006). Briefly, it was found that flight phase was minimal after *step 0* in the WRT and at the end of step-1 in the RWT. Therefore, the flight phase was suggested as an intrinsic dynamical constraint of human locomotion.

		Duration (ms)			Max1 (% BW)			Max2 (% BW)		
		Mean	*SD*	*Bonferroni*	*Mean*	*SD*	*Bonferroni*	*Mean*	*SD*	*Bonferroni*
WRT	*Stat*	p=.000	η²=.958		p=.000	η²=.942		p=.000	η²=.970	
	Step-3	592	16	-1,0,1,2,3	130.84	18.81	0,1	123.54	9.87	0,1,2,3
	Step-2	591	15	-1,0,1,2,3	136.92	19.46	0,1	122.99	10.41	0,1,2,3
	Step-1	573	27	-3,-2,0,1,2,3	141.52	13.22	0,1	112.02	12.27	0,1,2,3
	Step 0	430	34	-3,-2,-1,1,2,3	88.17	26.22	-3,-2,-1,1,2,3	173.57	20.89	-3,-2,-1,1,2,3
	Step+1	358	28	-3,-2,-1,0,2,3	120.31	15.37	-3,-2,-1,0,2,3	229.55	26.05	-3,-2,-1,0
	Step+2	326	15	-3,-2,-1,0,1	133.46	9.43	0,1,3	232.02	22.51	-3,-2,-1,0
	Step+3	323	23	-3,-2,-1,0,1	145.45	9.86	0,1,2	233.67	21.07	-3,-2,-1,0
RWT	*Stat*	p=.000	η²=.750		p=.000	η²=.734		p=.000	η²=.966	
	Step-3	354	19	-1,0,1,2,3	139.36	21.67	0,1	232.05	5.99	-1,0,1,2,3
	Step-2	330	16	0,1,2,3	133.26	19.49	0,1	222.83	11.87	0,1,2,3
	Step-1	386	30	0,1,2,3	138.44	12.01	0,1	207.17	8.94	-3,0,1,2,3
	Step 0	452	37	-3,-2,-1,1,2,3	194.82	22.95	-3,-2,-1,2,3	94.08	23.00	-3,-2,-1
	Step+1	513	27	-3,-2,-1,0,3	168.64	11.40	-3,-2,-1,2,3	107.22	9.91	-3,-2,-1
	Step+2	578	23	-3,-2,-1,0	145.00	11.49	0,1	116.27	6.16	-3,-2,-1
	Step+3	591	26	-3,-2,-1,0,1	135.41	11.96	0,1	117.10	5.34	-3,-2,-1

Table 1. Stance phase duration and Ground reaction force data.

The 'Stat'-line gives p and η² value of the repeated measures ANOVA with post hoc Bonferroni test.

			ICP			FFC			FFP			FFPOP		
			Mean	*SD*	*Bonf.*	*Mean*	*SD*	*Bonf.*	*Mean*	*SD*	*Bonf.*	*Mean*	*SD*	*Bonf.*
WRT		*Stat*	p=.000	η^2=.586		p=.000	η^2=.435		p=.000	η^2=.837		p=.000	η^2=.607	
	WS	*Step-3*	13.39	2.06	0,2,3	10.32	8.12	-	26.18	5.02	0, 1,2,3	49.31	5.84	1,2,3
		Step-2	14.13	2.21	0,2,3	10.95	4.82	0,1,2	25.58	4.80	0, 1,2,3	49.44	6.38	0, 1,2,3
		Step-1	14.64	2.92	0,2,3	13.64	5.54	0,1,2,3	21.93	3.92	0, 1,2,3	49.69	6.02	0, 1,2,3
	TS	*Step 0*	16.57	3.29	-3,-2,-1, 1,2,3	6.85	1.80	-2,-1	32.75	4.55	-3,-2,-1, 1,2,3	44.09	8.77	-2,-1, 3
	RS	*Step+1*	13.16	2.35	0,3	6.01	1.88	-2,-1	39.19	4.06	-3,-2,-1, 0	41.56	7.16	-3,-2,-1
		Step+2	11.67	2.08	-3,-2,-1, 0	6.08	2.32	-2,-1	41.82	5.46	-3,-2,-1, 0	40.51	6.35	-3,-2,-1
		Step+3	10.69	1.32	-3,-2,-1, 0,1	7.18	3.68	-1	44.22	5.82	-3,-2,-1, 0	38.21	9.79	-3,-2,-1 0
RWT		*Stat*	p=.128	η^2=.180		p=.000	η^2=.633		p=.000	η^2=.556		p=.009	η^2=.291	
	RS	*Step-3*	11.84	6.03	-	5.45	2.21	2,3	41.65	8.89	-1,0, 1,2,3	41.43	6.79	-1,2,3
		Step-2	11.17	2.28	-	5.68	1.70	2,3	38.77	5.70	1,2,3	44.67	5.33	1,2,3
		Step-1	11.99	6.46	-	4.86	2.42	2,3	36.04	7.23	2,3	47.74	5.39	-3
	TS	*Step 0*	11.02	1.78	-	5.24	1.66	2,3	31.52	7.28	-3,3	52.30	10.85	
	WS	*Step+1*	11.16	2.97	-	6.78	2.74	2,3	31.47	8.02	-2	50.44	7.24	-2
		Step+2	12.32	2.95	-	8.49	2.49	-3,-2,-1, 0,1	28.73	4.81	-3,-2,-1	50.30	3.85	-3,-2
		Step+3	12.96	3.16	-	10.20	3.25	-3,-2,-1, 0,1	25.00	3.50	-3,-2,-1	52.48	5.42	-3,-2

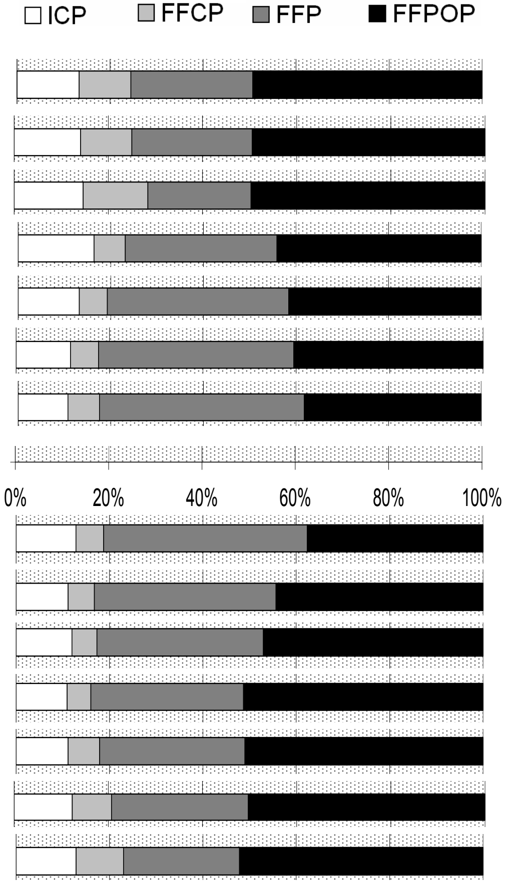


Table 2. COP Phases Statistics

The ‘Stat’-line gives p and η² value of the repeated measures ANOVA.

Bonf.= results of the Bonferroni post hoc test. The bars in the last column give a visual representation of data in the previous columns.

RS are characterized by a shorter FFPOP indicating that heel off occurs later in stance. This makes that push-off occurs quicker (relative and absolute timing) during the first RS after the WRT-step. Consequently, the first part of the foot unroll, associated with the touch-down and the adaptation of the foot to the ground, is longer in terms of percentage foot contact during RS. Nevertheless ICP and FFCP are also significantly shorter during RS (Table 2) associated to the faster plantar flexion inherent to a running pattern. Taken these two findings into account (shorter FFPOP, ICP and FFCP), the FFP is in terms of percentage of stance phase duration longer during RS. This gives the impression that weight transfer and subtalar eversion unlocking the foot occurs slower. Absolute duration, however, is equal which is reinforced by a similar speed (mean velocity during FFP) during RS and WS (Fig. 2). Hypothetically, this changed dynamics of the foot unroll or the duration of FFP might be a determinant of the WRT.

RWT

Our findings confirm the findings of Li and Hamill (2002) with a significantly lower active peak, needed to propel the body in the air, during step-1 in comparison to the previous RS. The pattern of the COM likely flattens and causes a smaller vertical peak during the TS compared to the previous RS. The likely smaller compression at touch down of the TS then might facilitate the switch from the flexion extension function of the stance leg during running to the pivot function of the stance limb during walking.

During step+1, the GRF showed a higher first peak and a lower second peak, compared to the following WS. Apparently a full stride (*step 0* and step+1) is necessary to realize the RWT, characterized by ‘transitional asymmetry’ in the double hump GRF-pattern. This ‘post’paration is in agreement with our expectations based upon previous findings (Segers et al., 2006). However, our hypothesis is not fully confirmed as changes during step-1 were not expected. This could be explained by the fact that external forces are more sensitive to the effect of summation of small kinematical changes during step-1 or by the treadmill used in previous research although the latter seems unlikely as Li and Hamill (2002) observed similar changes during step-1 on an instrumented Kistler treadmill.

Functional phases of the trajectory of the COP show similar changes as in the WRT although less significances were found due to high inter- and intravariability. Likely the WRT is a more compelling situation. The RWT allows for more variation as subjects are, without any doubt, capable of running below RWT-speed.

A limitation of the present study is that only vertical ground reaction forces were obtained. Future research should also record horizontal forces during actual acceleration across transition speed. Yet, these data fill a lacuna in the existing transition literature as the present results learn more about the actual realization of transition and the adaptation of the external forces to prepare and/or complete the transition.

In **conclusion**, human gait transitions are merely realized in one step. These transition steps (WRT and RWT) have a unique kinetic pattern evolving from one gait pattern to another. Kinetic recordings show a small preparation in the last step before the WRT- and RWT-step. In the RWT, adaptations are continued during the first step after transition. WRT and RWT clearly show different dynamics and should be studied as two distinct features in future transition-research.

ACKNOWLEDGEMENTS

This research was supported by BOF–RUG B/03796/01– IV1. The authors acknowledge Ing. P. Van Cleven & Ing. D. Spiessens for technical support. The authors also thank Ing. B. Jacobs and Lic. W. Lambrechts for online support (RsScan).

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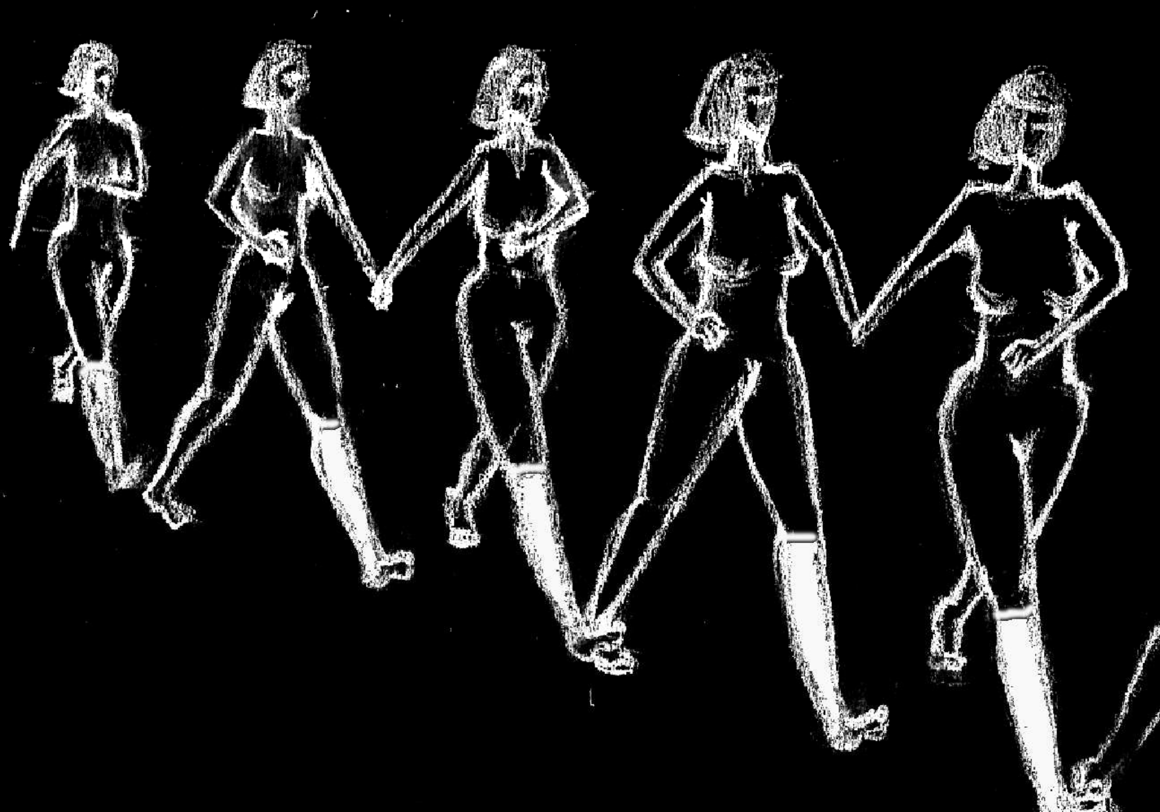
Chapter 6.

Influence of m. tibialis anterior fatigue on the walk-to-run and run-to-walk transition In non-steady state locomotion



ABSTRACT

The purpose of this study was to examine the influence of muscular fatigue of tibialis anterior (TA) on the walk-to-run transition (WRT) and run-to-walk transition (RWT) when speed is altered at different constant accelerations (a = 0.01, 0.07 and 0.05 m s^{-2}). Twenty women (height: 168.9 ± 3.36 cm) performed WRTs and RWTs on a motor-driven treadmill, before and after a protocol inducing muscular fatigue of the TA.

WRT-speed decreased after TA fatigue whereas RWT-speed did not change except during the intermediate deceleration. Integrated EMG (iEMG) of the activity burst of TA around heel contact was examined in the last steps before transition, the transition step and the first steps after transition. iEMG increased before WRT, then decreased after transition to running. In the RWT the opposite was observed: iEMG increased after RWT, then decreased with decreasing walking speed. After inducing fatigue in the TA, there was a decrease in iEMG in the WRT whereas no influence of fatigue was found on iEMG in the RWT.

As a result of TA fatigue, WRT occurred at a lower speed, probably to avoid over-exertion of the TA. This indicates that the TA is a likely determinant of WRT as previously reported. The RWT, on the other hand, was not altered following TA fatigue, which would indicate that WRT and RWT are determined by different factors.

Keywords: Gait transition, M. tibialis anterior, EMG, Biomechanics

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Accepted for publication in 'Gait and Posture'

INTRODUCTION

Increasing speed results in a change from walking to running. Decreasing speed on the other hand results in the opposite transition from running to walking (Hreljac, 1993a; Hreljac et al., 2001; Li and Hamill, 2002; Prilutsky and Gregor, 2001). Both transitions occur at a preferred speed (Hreljac, 1995a). Nevertheless, it is not yet entirely clear why humans prefer that specific speed to change from one mode to another (Raynor et al., 2002).

One of the most obvious reasons for the transition is metabolic cost, that is, a change to another type of locomotion reduces oxygen consumption. Regarding the relationship between metabolic cost and transition, conflicting results have been found. Some studies suggested that the walk-to-run transition (WRT) is closely linked to the minimization of metabolic cost (Hanna et al., 2000; Mercier et al., 1994). Others found evidence to reject this energy optimisation hypothesis (Brisswalter and Mottet, 1996; Hreljac, 1995; Hreljac et al., 2002; Minetti et al., 1994; Tseh et al., 2002). This contradiction can be partly explained by the difficulties in directly measuring the metabolic cost (Hanna et al., 2000; Raynor et al., 2002)

In the absence of a clear metabolic trigger, it is unclear why subjects perceive walking as ‘‘harder’’ than running at transition speed (Hreljac et al., 2002; Nobel et al., 1973). Subjects might use information from peripheral receptors, from the activity in the neural networks controlling locomotion, as well as from previous experience, to trigger transition and achieve a more comfortable mode of locomotion (Thorstensson and Roberthson, 1987). This is supported by evidence showing that perceived effort during low intensity exercise (estimated by the rate of perceived exertion) originates from motor outflow commands to muscles (quantified by muscle activation) and, to a lesser degree, from the afferent information of the actual force developed by the muscles (McCloskey et al., 1983).

The larger, proximal muscle groups are not activated near their maximal level when walking or running at a speed close to WRT-speed. Therefore, muscular activation level and muscular stress level is low (Hreljac, 1993; Hreljac et al., 2001). The smaller and distal tibialis anterior muscle (TA), however, is activated near its maximum capacity and experiences high muscular stress around WRT-speed (Hreljac et al., 2001). The amplitude of peak EMG of the TA increased with increasing walking speed but suddenly decreased after transition (Hreljac et al., 2001). Also, at WRT-speed, critical levels of ankle angular velocities and accelerations are reached (Hreljac, 1995; Prilutsky and Gregor, 2001). This apparently crucial role of the TA led to the hypothesis that the WRT is determined at the ankle region (Hreljac, 1995; Hreljac et al., 2001). EMG of the TA during walking and running has a typical phasic activity pattern with a burst during the eccentric foot plantarflexion movement following heel contact. This eccentric activity may be causing an increased perceived exertion, which would serve as protective mechanism to prevent further damage (Hampson et al., 2001).

Although WRT may be triggered by information arising around the ankle region, this may not necessarily be the case for run-to-walk transition (RWT). The ankle velocity and acceleration change from a lower value in running to a higher value in walking (Hreljac, 1995). Therefore, Prilutsky and Gregor (2001) suggested that RWT might be controlled by other muscle groups, namely the muscles active during stance (soleus, gastrocnemius and vastus lateralis). The perception of increased effort in these support-related muscles is likely to be required for the acceleration and deceleration of the body’s centre of mass and the larger peaks of vertical ground reaction forces (Prilutsky and Gregor, 2001; Nilsson et al., 1985).

The purpose of this study was to examine transition speed and activity of the TA in a protocol with gradually changing speed to investigate the actual transition step(s) when accelerating across transition speed. By inducing fatigue in the TA, local perceived exertion is expected to increase (Kent-Braun et al., 2002) which then decreases WRT-speed (Hreljac et al., 2001).

The main hypotheses of this study are: (1) WRT occurs at a lower speed following TA fatigue, while RWT remains unaffected, (2) integrated EMG (iEMG) will increase as walking speed increases in the WRT, then decrease after WRT, both before and after TA fatigue and (3) TA activity in the RWT will not be affected by transition nor by TA fatigue.

MATERIALS AND METHODS

1. Subjects

20 physically active female human subjects took part in the present research after having signed informed consent (Table 1). Subjects were selected on sex, age and height. Although only weak correlations were found between anthropometric variables and transition speed, stature was chosen between 1.65 m and 1.75 m to minimize possible influence of anthropometry (Hanna et al., 2000; Hreljac, 1995b; Raynor et al., 2002). At the moment of the study all subjects were free from any disease or injury that might have affected the results. The ethical committee of the Ghent University Hospital approved the experimental protocol.

	X	SD
Height (cm)	168.9	3.4
Weight (kg)	63.2	5.9
Leg length (cm)	91.4	1.8
Age (years)	24.5	2.8
Physical activity (hours/week)*	2.82	0.95

Table 1. Subjects characteristics: mean (X) and standard deviation (SD) for height, body mass, leg length and age. * Sports on competitive level

2. Treadmill protocol

The experiment was divided in 2 sessions. Each session, every subject performed 30 trials divided in 6 blocks of 5 trials with a resting period of 30 seconds between each block. Each block was characterized by a constant acceleration. This type of protocol with gradually changing speed is chosen because transition might be a process (Li and Hamill, 2002; Segers et al., 2006) with acceleration as an important task constraint (Li, 2000). The accelerations were 0.10, 0.07, 0.05, -0.10, -0.07 and -0.05 m s^{-2}. Positive and negative accelerations, respectively, caused WRT and RWT. By choosing these magnitudes, the acceleration at which WRT-speed equals probably RWT-speed (no hysteresis at 0.07 m s^{-2}: Li, 2000) was included as well as distinctly lower (0.05 m s^{-2}) and higher (0.10 m s^{-2}) values. The blocks were randomly provided to the subjects but alternating positive and negative accelerations. The first block was not incorporated in the calculations but was considered a familiarization trial block.

The first session, all subjects were familiarized with the treadmill by performing treadmill locomotion at different speeds for at least 15 minutes (Wall and Charteris, 1980). The second session began with the fatigue-inducing protocol followed by the treadmill protocol. The time elapsed between the fatigue-inducing and treadmill protocol was maximally two minutes to exclude potential recovery of TA.

The actual speed of the treadmill was on-line electronically registered (5Hz) and synchronized with video recordings by means of LED's.

3. Fatigue protocol

Subjects were seated on a chair with thighs and trunk strapped to the chair in order to eliminate the undesired use of these segments in the fatigue protocol. A submaximal load (± 70% 1 Repeated Maximum) was placed on the Tib Exerciser, a fitness device used to train the TA. Subjects were asked to move the load up and down at a constant speed. This was supervised by an experienced researcher to create a standardized protocol. Subjects performed series of 15 repetitions with a 30 seconds break between successive series, until exhaustion was reached. If a series was not completed, subjects got a second try after a 1 minute break. A Borg scale (scale 1-10), adapted for localized muscular fatigue, was used to scale muscle fatigue (Borg, 1998).

4. Instrumentation

EMG of TA was recorded over 8 seconds at a sampling frequency of 1000 Hertz using bipolar electrodes (Noraxon). Data of the TA were rectified, bandpass filtered (5-2000 Hz) and integrated. Hreljac et al. (2001) calculated mean and peak 100-ms moving average activation levels and found that there was an abrupt transition related change to a lower value in the peak EMG-values. EMG of the TA in the activation burst in vicinity of heel contact is examined by integrated EMG (iEMG) in the present research. iEMG was normalized to the value of *step 0* in the WRT and is the product of magnitude and duration of the burst. In the approach towards transition more intensive activation of TA results in a higher recruitment level of the muscle, which will be reflected in iEMG.

Sagittal plane films, focussed on the leg movement, were measured during all trials using a high-speed video camera (JVC DVL9800) at 200 Hz. The moment of initial (heel) and final (toe-off) contact of the foot were determined from the recordings. Step frequency (SF) was calculated as 1/Δt (Δt = the time between two successive foot contacts). Step length (SL) was calculated by dividing instant speed of treadmill by SF. Duty factor (DF) was the ratio of contact-time and total stride time (Zatsiorsky et al., 1994), a parameter used to define walking ($DF > 0.5$) and running ($DF < 0.5$). The transition step was called step zero (0) and was defined as the first step with a flight phase when speed was increased (WRT) or the first step with a double stance phase when speed was decreased (RWT). Every step before transition had a negative sign; every step after transition had a positive sign.

From the video images, the foot angle (angle shoe sole- horizontal treadmill belt) was calculated. A marker was placed on the lateral malleolus and on metatarsal 5, and standardized tight fitting running shoes were used.

5. Statistics

All data were stored and analyzed using the SPSS 11.0 package (SPSS inc., Chicago, Il). Descriptive statistics (mean ± SD) were calculated for subjects' characteristics, speed (v), duty factor (DF), step length (SL) and step frequency (SF), rate of perceived exertion (RPE), number of series, iEMG, duration and magnitude of the bursts, amplitude of the EMG-signal and foot angle.

A paired sample T-test was used to evaluate the differences in RPE before and after fatigue. The analyses to compare v, DF, SL, SF, iEMG, duration and magnitude of the burst were done in a step wise protocol. iEMG before fatigue was examined by a repeated measures analysis of variance (ANOVA) with a Bonferroni test to compare the 11 steps (step-5 to step+5) pair wise. Two (negative versus positive acceleration) by two (before and after fatigue) by three (accelerations 0.10 m s^{-2}, 0.07 m s^{-2}, 0.05 m s^{-2}) repeated measures ANOVAs were performed to test for differences in transition speed. Since an interaction was found between WRT and RWT, throughout the rest of the paper, two (fatigue) by three (acceleration) repeated measures ANOVAs were performed to test for effects in WRT and RWT for each step (step-5 to step+5) separately.

The 2*3 repeated measures ANOVA revealed significant effects of fatigue in step-1, *step 0* and step+1 and not in the preceding or following steps. Therefore, effects of fatigue were reported for these steps only. Effect size was estimated by a squared partial eta (η^2) which expresses the amount of variance, as a fraction of the total amount of variance that can be explained by a certain effect (i.e. step or fatigue).

Non-parametric statistics were used to explore differences in foot angle for 5 randomly selected subjects. A Friedman test was used for differences between walking, running and transition steps (related samples) whereas a Mann-Whitney-U test was used for examination of the influence of TA fatigue.

RESULTS

1. Fatigue protocol

The perceived exertion of the TA (from an adapted Borg scale) increased significantly during the fatigue protocol (Table 2). After fatigue, subjects were no longer capable of lifting the weight in a controlled manner, even after encouragement and a resting period of 60 seconds.

		X	SD	
RPE	Before fatigue protocol	2.16	0.78	
	After fatigue protocol	9.33	0.34	**
Series	Number of series completed	10.79	2.58	

Table 2. Rate of perceived exertion (RPE) on the adapted Borg scale before and after the fatigue protocol and number of series completed during the fatigue protocol.
Mean X and standarddeviation SD. Significant difference between RPE before and after fatigue **p<0.01

2. Transition speed (Table 3)

After introducing localized muscular fatigue in the TA, WRT-speed was significantly lower in all accelerations ($F_{1,14}$=35.341, p<0.01, η^2=.716). Rate of acceleration did not affect WRT-speed ($F_{2,28}$=2.142, p=.136, η^2=.133) or interact with fatigue ($F_{1,14}$=.772, p=.472, η^2=.052).

In the RWT-condition, however, there was an interaction between fatigue and acceleration ($F_{2,28}$=6.725, p<.001, η^2=.324). RWT-speed was increased after fatigue in the intermediate deceleration.

		Transition Speed (m s^{-1})	
	Acceleration	*Before fatigue*	*After fatigue*
WRT	*0.1 m s^{-2}*	2.16 ± 0.12	2.06 ± 0.07**
	0.07 m s^{-2}	2.10 ± 0.06	2.00 ± 0.07**
	0.05 m s^{-2}	2.12 ± 0.08	2.04 ± 0.09 **
RWT	*-0.1 m s^{-2}*	2.19 ± 0.14	2.19 ± 0.14
	-0.07 m s^{-2}	2.12 ± 0.09	2.20± 0.14**
	-0.05 m s^{-2}	2.17 ± 0.06	2.18 ± 0.06

Table 3. Transition speed before and after fatigue for all accelerations (mean ± standard deviation). Significant difference between transition speed before and after fatigue ** p<0.01.

3. EMG unfatigued

EMG before fatigue was studied in the last steps before and the first steps after transition.

WRT

The repeated measures ANOVA revealed significant effects for normalized iEMG between step-1 and step+1 (p<0.05), whereas only few significant differences were found in all other steps. As can be seen in figure 1, iEMG increased during the last walking steps before transition, and dropped to a lower value after transition. In the 2 lowest accelerations, iEMG increased again in the following running steps.

RWT

Normalized iEMG remained approximately constant in the last running steps, increased at transition to decrease again after some walking steps. iEMG was higher in the first steps after transition in comparison to the last running steps (Fig. 2). After step3, iEMG decreased to the level observed during the running steps in the two highest decelerations.

4. EMG fatigued

Changes in EMG activity of the TA in proximity of heel contact is examined after fatigue to identify possible underlying mechanisms of the TA as a determinant of WRT and/or RWT.

WRT

iEMG significantly decreased after muscular fatigue in step-1 and *step 0* (Table 4, Fig. 3), with an effect of acceleration in step-1. In step+1, on the other hand, fatigue did not affect iEMG. The η^2-value, which explains the importance of the fatigue effect, is small (0.02). No further analyses were done to reveal effects of fatigue in step+1.

The duration of the burst was significantly lower after fatigue in step-1 and *step 0*, with a difference between accelerations (Table 4) but no interaction between fatigue and acceleration. In step+1, the duration of the burst was affected neither by fatigue of the TA nor by the rate of acceleration. Also here there was no interaction-effect between fatigue and acceleration (Table 4).

After fatigue, the magnitude of the burst increased in step-1 and *step 0*, whereas no effects were found in step+1 (Table 4). The acceleration, on the other hand, affected the magnitude of the signal in all three steps (Table 4). No interaction was found in step-1 and *step 0*.

RWT

In step-1, there was one main effect of acceleration on iEMG ($F_{2,24}$=6.43, p=0.01, η^2=0.35) and a main effect of both acceleration ($F_{2,24}$=15.48, $p<0.01$, η^2=0.56) and fatigue ($F_{1,12}$.=5.26, p=0.04, η^2=0.31) on magnitude of the burst. In step+1 there was a main effect of acceleration on magnitude ($F_{2,24}$=9.33, p=0.01, η^2=0.44) and duration of the burst ($F_{2,24}$=5.69, p=0.03, η^2=0.32). No interaction effects between fatigue and acceleration were found. η^2 values were lower for the RWT compared to the WRT.

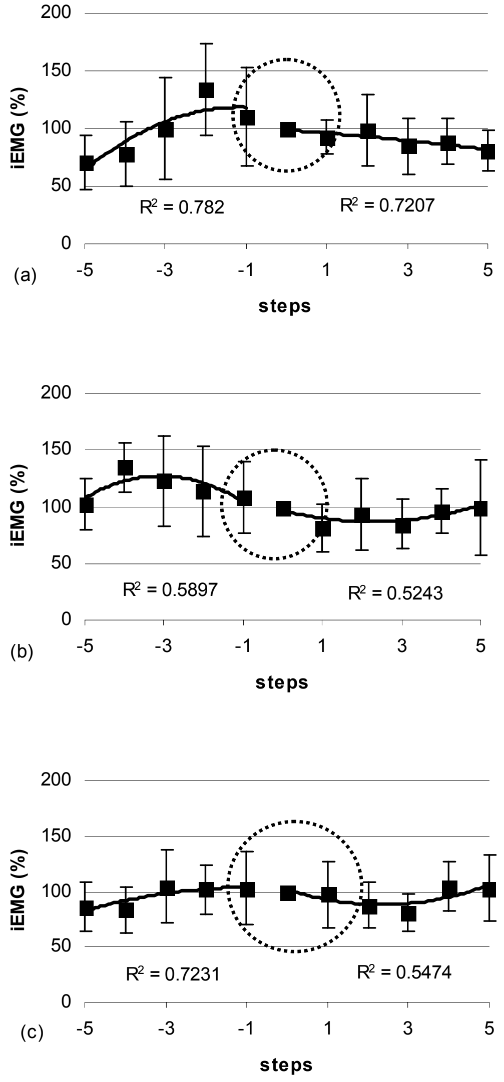

Figure 1. Evolution of normalized iEMG of the burst of TA activity in proximity of heel contact in the WRT

(a) a = 0.10 m s^{-2}
(b) a = 0.07 m s^{-2}
(c) a =0.05 m s^{-2}

iEMG of the TA in the burst at heel contact was normalized to the value at *step 0* in the WRT (with corresponding acceleration) for each subject.

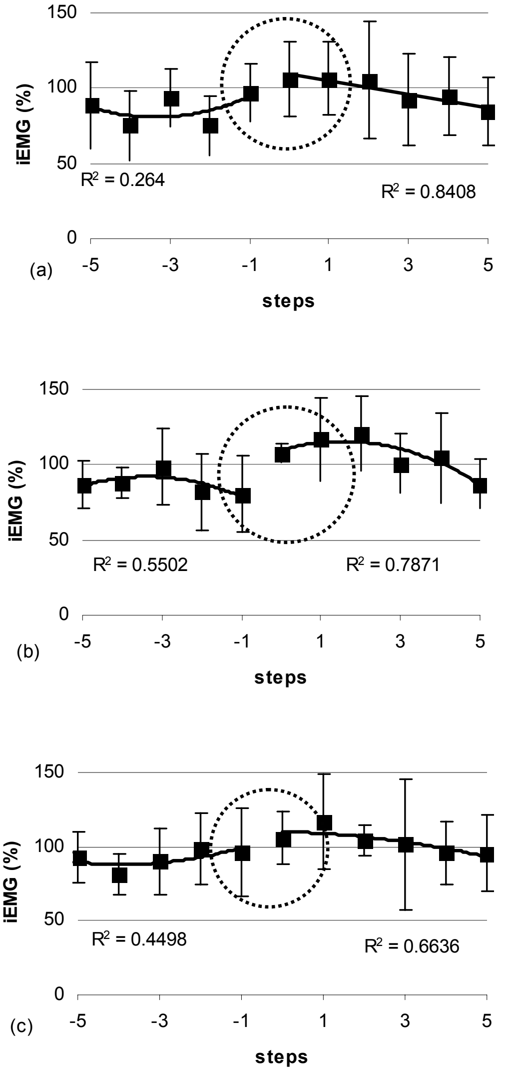

Figure 2. Evolution of normalized iEMG of the burst of TA activity in proximity of heel contact in the RWT

(a) a = - 0.10 m s^{-2}
(b) a = - 0.07 m s^{-2}
(c) a = - 0.05 m s^{-2}

iEMG of TA in the burst at heel contact was normalized to the value at *step 0* in the *WRT* (with corresponding acceleration) for each subject.

Figure 1 & 2: iEMG – values in the graphs represent the mean and standard deviation of all normalized averages of the subjects. Statistics were only applied in the zone step-1 to step+1, as that is the region of interest. To give the reader a clear view on the data, however, the progress of iEMG is given from step-5 to step+5 with R² values indicating the accuracy of the regression line.

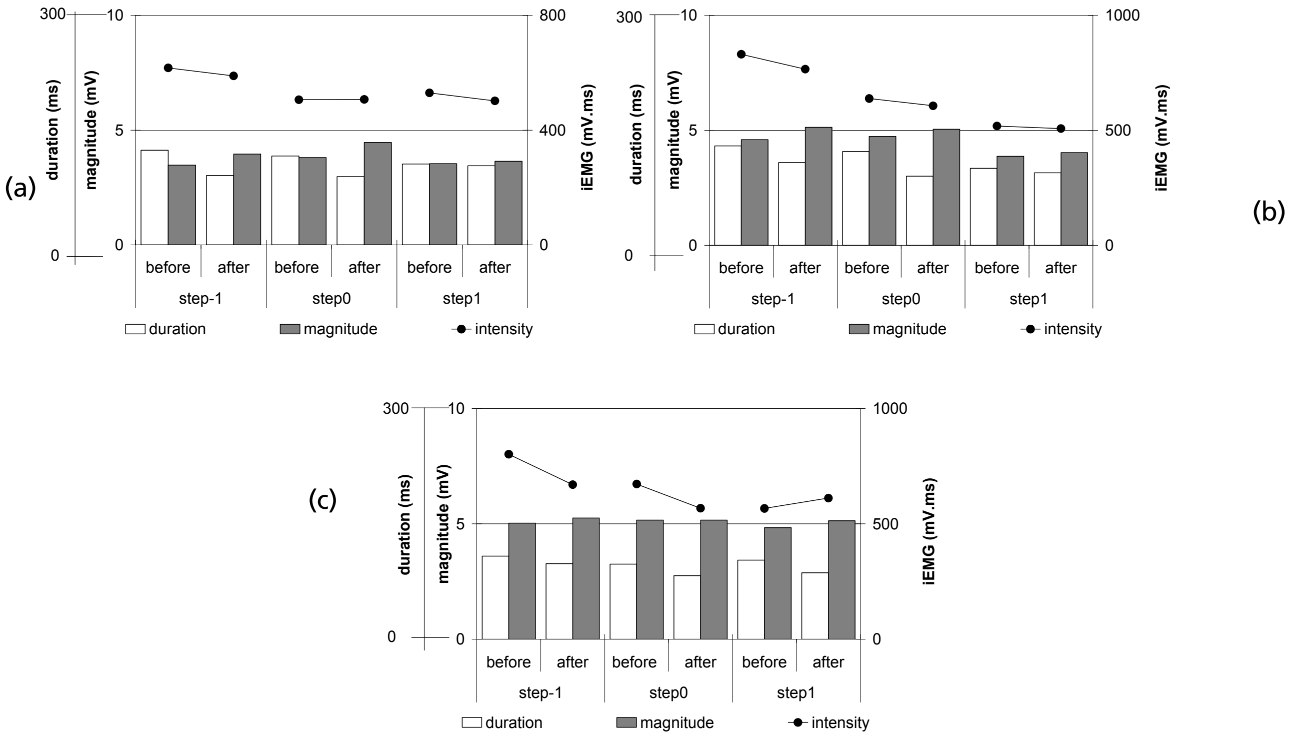

Figure 3. Integrated EMG (iEMG) of the tibialis anterior before and after fatigue in the WRT

(a) a = 0.10 m s^{-2}

(b) a = 0.07 m s^{-2}

(c) a = 0.05 m s^{-2}

iEMG (intensity= mV. ms) is the product of magnitude (mV) and duration (ms) of the burst.

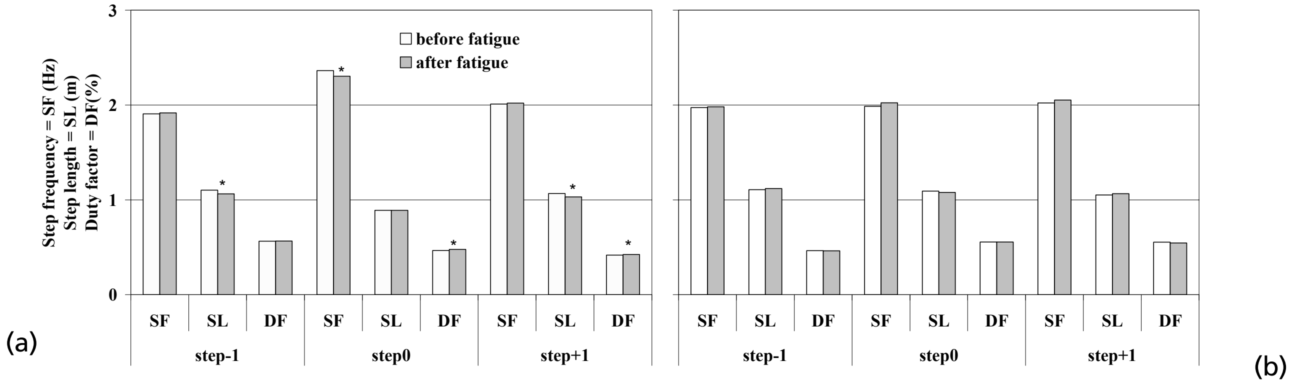

Figure 4. Spatiotemporal factors before and after fatigue in (a) WRT and (b) RWT.

Asteriskes indicate significant differences (*= $p<0.05$). There are no significant differences in spatiotemporal factors between the accelerations (no differences in transition speed either). Therefore, no distinction is made between the accelerations. Bars represent the average of (a) all accelerations in the WRT-protocol and (b) all decelerations in the RWT-protocol.

5. Spatiotemporal factors

WRT

SF was significantly lower after fatigue in the transition step ($F_{1,12}$=7.09, p=.026, η^2=.441). In step-1 and step+1 SF remained unchanged (Fig. 4a).

There was a main effect of fatigue on SL in step-1 ($F_{1,12}$=6.12, p=.033, η^2=.380) and in step+1 ($F_{1,12}$=7.74, p=.019, η^2=.436) with SL significantly lower after fatigue. There were no main effects or interaction-effects on SL in the transition step (Fig. 4a). DF in step-1 was not changed, neither by the degree of acceleration nor by muscular fatigue. In *step 0*, a main effect of acceleration ($F_{2,24}$=4.55, p=.036, η^2=.452) and fatigue ($F_{1,12}$=8.85, p=.012, η^2=.424) on DF was found and no interaction between both. In step+1 DF was lower after fatigue ($F_{1,12}$=7.24, p=.020, η^2=.376).

RWT

In step-1 no effects were found for SF (Fig. 4b). In *step 0* an interaction-effect of acceleration and fatigue was found ($F_{2,24}$=15.47, p=.001, η^2=.738). In the highest deceleration a decrease in step frequency in found, opposed to the increase in the other decelerations. The degree of acceleration had a main effect on SF in step 1 ($F_{2,24}$=7.22, p=.010, η^2=.568). SL was unchanged in step-1 and *step 0*: no main or interaction effects were found for acceleration and fatigue. In step 1 an interaction-effect was found ($F_{2,24}$=4.75, p=.033, η^2=.463): an increase in the highest acceleration, a decrease for the two lowest decelerations. For DF a main effect of acceleration was found in step-1 ($F_{2,24}$=8.19, p=.007, η^2=.598) and step+1 ($F_{2,24}$=6.94, p=.011, η^2=.558).

6. Foot angle (Table 5)

To explore possible influences of muscular fatigue of the TA on the foot angle (shoe sole-ground), foot angle was calculated for 5 randomly selected subjects. As can be seen table 5, there is a decrease in foot angle after WRT. No differences for fatigue were observed.

	acceleration			Fatigue			interaction		
	F(2,24)	p	η^2	F(1,12)	p	η^2	F(2,24)	p	η^2
					iEMG				
Step-1	7.69	0.00	0.40	4.60	0.05	0.28	0.02	0.98	0.00
Step 0	1.09	0.35	0.08	22.84	0.00	0.66	0.12	0.89	0.01
Step+1	1.77	0.21	0.13	0.28	0.76	0.02	4.03	0.03	0.25
					duration				
Step-1	4.75	0.02	0.28	13.64	0.00	0.53	2.86	0.08	0.19
Step 0	4.48	0.02	0.27	13.84	0.00	0.54	0.41	0.67	0.03
Step+1	2.83	0.12	0.19	1.62	0.22	0.12	0.21	0.81	0.02
					magnitude				
Step-1	31.97	0.00	0.73	21.11	0.00	0.64	3.04	0.07	0.20
Step 0	5.62	0.01	0.32	19.11	0.00	0.61	2.47	0.11	0.17
Step+1	5.66	0.03	0.33	0.04	0.97	0.00	5.61	0.01	0.32

Table 4. Main and interaction effects found by the repeated measures analysis for step-1, *step 0* and step+1 in the WRT

	Foot Angle ($a=0.10$ m s^{-2}) (n=5 - 25 trials)	
	Before fatigue	*After fatigue*
Walking steps	34.92 ± 2.57	32.32 ± 1.99
Transition step	23.56 ± 2.57*	25.85 ± 2.38*
Running steps	24.15 ± 2.15*	22.74 ± 1.78*

Table 5. Touch down angle of the foot (shoe sole/ground) in the WRT
*Significant difference ($p<0.05$) with foot angle during walking steps

DISCUSSION

Our main hypotheses were confirmed. (1) The WRT-speed was significantly decreased after fatigue of TA. RWT-speed did not change except for the intermediate deceleration. (2) In the WRT, iEMG increased with increasing walking speed, then decreased after the transition to the running gait. The third hypothesis was only partially confirmed as (3) in the RWT, no effect on iEMG was found for fatigue. However, an effect of transition was observed as iEMG increased during the transition step, and then decreased with decreasing walking speed.

Below, we will first separately discuss the WRT and RWT, in order to come to a general discussion at the end.

1. Walk-to-Run Transition

The main finding was that WRT-speed is lower after localized fatigue of the TA (Table 3). The decrease of WRT-speed with fatigue was related to a significant decrease in SL (Fig. 4a). SF, on the other hand, remained constant after fatigue, except for the transition step. DF was higher in the transition step and the first running step, indicating that there is a longer contact with the ground. Segers et al. (2006) described the evolution of the spatiotemporal parameters in a protocol with gradually changing speed and identified the WRT-step as an outlier. As can be seen in figure 4, SF of the transition step still differs from the previous walking steps and the following running steps after fatigue and is the only step where speed was altered by a decrease in SF.

The pattern of the iEMG followed the hypothesized pattern for the TA. iEMG rose before transition, then dropped to a lower value *after transition* (Fig. 1). The amplitude and duration of the isolated burst of concentric-eccentric activity of the TA in proximity of heel contact reduced after transition (Fig. 3), reinforcing the theory of Hreljac (2001). By fatiguing the muscle, TA would experience a feeling of local discomfort probably causing transition (Hreljac et al., 2001).

Hreljac linked his ‘maximal stress theory’ to the maximal amplitude of the EMG-signal. Therefore, to give further explanatory information the maximal amplitude of the rectified EMG-signal (before fatigue) was studied for 5 subjects. This confirmed the findings of Hreljac et al. (2001). The maximal amplitude is lower after transition to the running gait. Despite this finding, iEMG provided us with more information about the RPE. Since RPE consists of a central and a local factor (Noble et al., 1973), localized muscular overexertion of the TA was greater during walking due to the periodic burst of high activity in comparison to the longer periodic burst of moderate activity in running (Hreljac et al., 2001). Peak EMG, however, does not fully provide the information needed to describe a periodic burst of TA activity as it was momentary information. iEMG gave more profound information about burst activity, indicating that the burst in proximity of heel contact was indeed lower after transition to running.

One of the most remarkable differences between walking and running at speeds in proximity of the transition-speed was the touch down angle of the foot that was smaller during running (Table 5 & described in literature by: Nilsson et al., 1985; Sasaki and Neptune, 2006). It is expected that this introduced a less demanding situation for TA activity.

After fatigue, there was a decrease in iEMG related to the duration of the burst (Fig. 3, Table 4). The mean amplitude of the burst was higher but could not compensate for the decrease in duration. After fatigue, a similar evolution in the iEMG in approach to the WRT and a decrease in the maximal amplitude after transition was found. Muscular fatigue is known to increase the sense of effort in the muscle (Kent-Braun et al., 2002), probably causing the decrease in WRT-speed. After fatigue the force-generating capacity, needed to place the foot in a controlled manner and prevent the foot from slapping down (Cole et al., 1996; Flynn et al., 2004; Gefen, 2001; Perry, 1992), was reduced.

Taking into account that the touch down angle of the foot was lower during running (Table 5), this indicated that there might have been a tendency to change the mode of locomotion sooner with fatigued TA in order to avoid the larger eccentric action needed to lower the foot during walking.

TA fatigue influences the loading rate of the vertical GRF in steady-state running (Christina et al., 2001; Gefen, 2001). An increased loading rate was also one of the typical characteristics of the last steps before the (WRT) in a protocol with gradually increasing speed (Li and Hamill, 2002). Does that mean that loading rate of GRF is the link between TA fatigue and lower WRT-speed?

Another possible explanation could be the greater instability of the foot after TA fatigue (Cole et al., 1996). At heel contact, everting load was maximized in walking (Cole et al., 1996; Perry, 1992). If this eversion of the foot was insufficiently counteracted by muscle force of the TA, with secondary function inversion (Cole et al., 1996; Gefen, 2001; Perry, 1992), this will cause a medial shift of the centre of pressure and a lateral shift of the centre of mass (Cole et al., 1996; Gefen, 2001). Maybe an earlier transition to running is linked to this subjective feeling of instability.

However, we wish to emphasize that this signal -TA- is only one among a whole pool of gait determinants and could be overruled by other factors, like fear or visual flow (Malcolm et al., 2005; Mohler et al., 2004).

2. Run-to-Walk Transition

RWT-speed was altered after fatigue in the intermediate deceleration. The interaction effects between fatigue and acceleration can be explained by this difference between decelerations. This discrepancy could be due to the fact that the RWT is less urgent than the WRT (Hanna et al., 2000). In the WRT there was a local discomfort in the dorsiflexor area whereas in the RWT there was no such feeling of discomfort (Prilutsky and Gregor, 2001). If wanted, subjects could run easily at a lower speed, whereas the occurrence of the WRT was limited. Therefore, variability in RWT through conscious decision making might be higher (Table 2) (Prilutsky and Gregor, 2001).

The protocol of gradually changing speed allowed us to describe RWT, in contrast to some previous studies (Hreljac, 1993a, 1993b, 1995a, 1995b; Hreljac et al., 2001, 2002; Minetti, 1994; Prilutsky and Gregor, 2001). As can be seen on figure 2, iEMG increased *after transition*, mostly due to an increase in the duration of the burst before heel contact. Fatigue of the TA did not change iEMG. The pattern of the iEMG indicated that the TA is probably not a determining factor for the RWT, as in walking it reaches a higher activation level that can be coupled to the larger touch down angle of the foot (Table 5).

In future research, it could be interesting to take a closer look at the transition phenomenon (WRT and RWT) in an overground condition. In the present study walking/running on a treadmill was chosen because of the protocol with gradually changing speed. It could be that transition-speed (WRT and RWT) is altered by the use of the treadmill (Johnson and Li, 2000; Malcolm et al., 2005) because (1) the treadmill induces changes in kinematic variables, which are associated to transition, i.e. foot and ankle angle (Savelbergh et al., 1998; Wank et al., 1998), (2) power flows from the athlete to the treadmill and vice versa (Savelbergh et al., 1998; Shamhart et al., 1994) and (3) spatiotemporal characteristics are influenced by the treadmill (Stolze et al., 1997; Wank et al., 1998). Furthermore, studying transition overground enables ground reaction forces measurements using the standard technology of force plates. Inverse dynamics then allow for calculation of the net joint powers that are associated to muscular activity levels.

Hreljac (1995a) showed that at transition critical levels of ankle angular velocities and accelerations are reached. According to Hreljac et al. (2001), the dorsiflexors would work at their maximal capacity to produce these large angular accelerations and changing gait (WRT) would alleviate the local perceived exertion on the dorsiflexors. Recent modelling of Neptune and Sasaki (2005), however, showed that plantar flexors are important determinants of the WRT. Taken these two opinions into account and knowing that the ankle moment is the sum of the moments about the ankle joint from the forces developed by both agonists and antagonists, it could be that the present study is hampered by altered antagonist activity.

3. Conclusion

The main finding was that WRT-speed is lower after fatigue, whereas RWT-speed is not altered. Integrated EMG in the WRT is lower after transition to the running gait, reinforcing the theory of Hreljac (2001) in a protocol with gradually changing speed. TA is a likely candidate to determine the WRT. In the RWT no differences were found, leading to the conclusion that WRT and RWT are two different mechanisms with different underlying factors.

ACKNOWLEDGEMENTS

This research was supported by BOF–RUG B/03796/01– IV1. The authors acknowledge Ing. P. Van Cleven and Ing. D. Spiessens for data collection and technical support and Lic. A. De Cock and Dr. J. Vanrenterghem for their professional advice. The authors also thank Prof. Dr. D. Adriaens (Ghent University, department of Vertebrate Morphology & Zoology Museum) for the use of the JVC highspeed camera.

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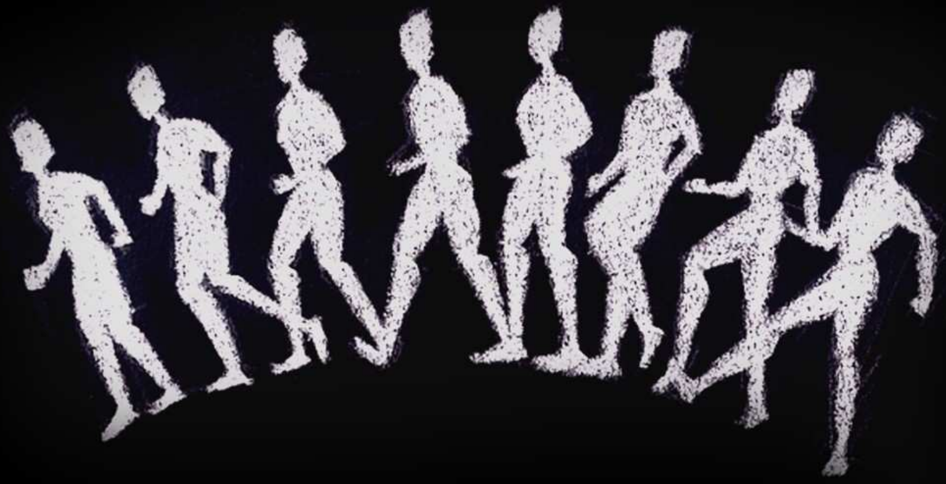

Chapter 7

General discussion

INTRODUCTION

The main purpose of the present research was to gain insight in the actual realization of transition. In order to meet this objective, human gait transitions were examined using a protocol with gradually changing speed. Subjects accelerated or decelerated across transition speed with constant acceleration. To get a comprehensive detailed view on the execution of transition, spatio-temporal factors, kinematics, dynamics of the body centre-of-mass and external forces were examined. Unfortunately, within the time frame of this thesis, it was impossible to study net joint moments or powers as well.

One of the main findings of the present thesis is that the walk-to-run transition (WRT) and run-to-walk-transition (RWT) are not realized in the same manner: in other words they show –as we called it in the chapter 2 on spatio-temporal characteristics– “functional hysteresis”. Taking this into account, both transitions will be discussed separately. Furthermore, for the purpose of this general discussion, we will integrate all studied variables dealt within the successive chapters. Afterwards, a comparison between WRT and RWT shall be made.

A second purpose was to take a deeper look at one of the determinants of human gait transitions, perhaps unravelling one of the reasons why humans change their gait pattern. By influencing one of the possible determinants of transition (m. tibialis anterior), the effect of disturbance on the natural transition environment was examined. This will be discussed using the insights as put forward in the first part of the discussion.

In the last part of the discussion, limitations of the present research shall be described and suggestions for future research on the transition phenomenon made, hoping to inspire future research in this area.

PART 1. HOW DO HUMANS REALIZE GAIT TRANSITIONS?

WALK-TO-RUN TRANSITION

Increasing speed leads to a walk-to-run transition (WRT) that occurs below the energetically optimal cross-over point and below the maximal walking speed (Hanna et al., 2000; Raynor et al., 2002; Segers et al., 2006).

	WRT-speed		
		Speed ($m\ s^{-1}$)	
Protocol	*Acceleration* ($m\ s^{-2}$)	*X*	*SD*
Treadmill *(Chapter 2-3)*	0.1	2.16	0.12
	0.07	2.10	0.06
	0.05	2.12	0.08
Overground *(Chapter 4-5)*	0.17	2.17	0.12

Table 1. WRT-speed on a treadmill and overground

From literature is known that this WRT-speed can be influenced by the acceleration magnitude (Li, 2000) and the use of a treadmill (Johnson and Li, 2000; Malcolm et al., 2005). In the present research, however, we did not find differences, neither between different accelerations nor between overground and treadmill conditions (Table 1). One of the draw backs in the latter comparison is the difference in acceleration magnitude and perhaps even more important the different subjects used in both studies. Therefore, the present comparison must be interpreted cautiously. One of the benefits of the similar transition speed in both protocols is that kinematics and kinetics of the transition step and the steps in the transition zone (steps in a range around the transition step) can now be compared without taking potential speed effects into account. However, this does not exclude possible effects of the treadmill acceleration on kinematic variables. In the following paragraphs, differences in the transition step between overground and treadmill acceleration across transition speed (point 1) shall be addressed followed by a detailed review of all studied variables in approach to the transition step (point 2).

1. The transition step

In general, we found that WRT is mainly realized in the transition step (*step 0*) during which energy is actively generated to initiate the first flight phase (spatio-temporal running). This is accompanied by the switch from an out-of-phase to an in-phase organization of gravitational potential and kinetic energy of the centre-of-mass (COM) (dynamical running). Because the transition step is also characterized by flexion of the stance limb (kinematic running), the three definitions of the transitions from walking and running (spatio-temporal, dynamical and kinematic) concur even in proximity of the WRT-step (Fig. 1).

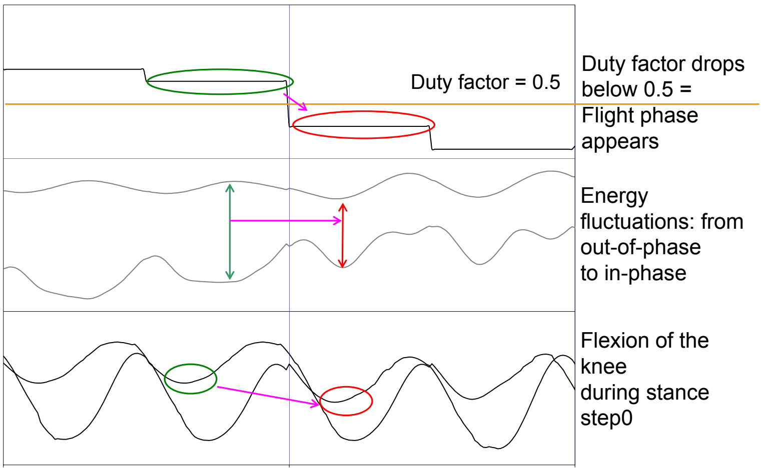

Figure 1. The three definitions of the WRT-step

The upper panel represents the duty factor (spatio-temporal definition), the middle panel the energy fluctuations of the COM (dynamical definition), the lower panel the knee-angle (kinematic definition). All variables are 'treadmill' data (a = 0.1 m s^{-2}) within the interval from step-2 to step+2.

Putting all results together, allows comparing the transition step during overground and treadmill acceleration across transition speed (Fig. 2). Opposed to the few and often small kinematic differences found between overground and treadmill conditions during steady-state walking and running (Alton, 1998; Nigg et al., 1995; Savelbergh et al., 1998; Shamhart et al., 1994; Stolze et al., 1997; Wank et al., 1998), several significant differences can be found during the WRT-step (Fig. 2a).

Compared to an overground WRT-step (red stick figure, Fig. 2a), less knee flexion at midstance, more knee extension at toe-off, less ankle plantar flexion at toe-off and more hip flexion throughout stance can be observed in the WRT-step on the treadmill (grey stick figure, Fig. 2a). These differences, however, should be considered into the right perspective because (1) these are averaged data for different subjects and trials, (2) only the key events (heel contact, end double stance, midstance and toe-off) are presented in the stickfigure and (3) accelerations to be generated by the subjects were different (on the average: Table 1).

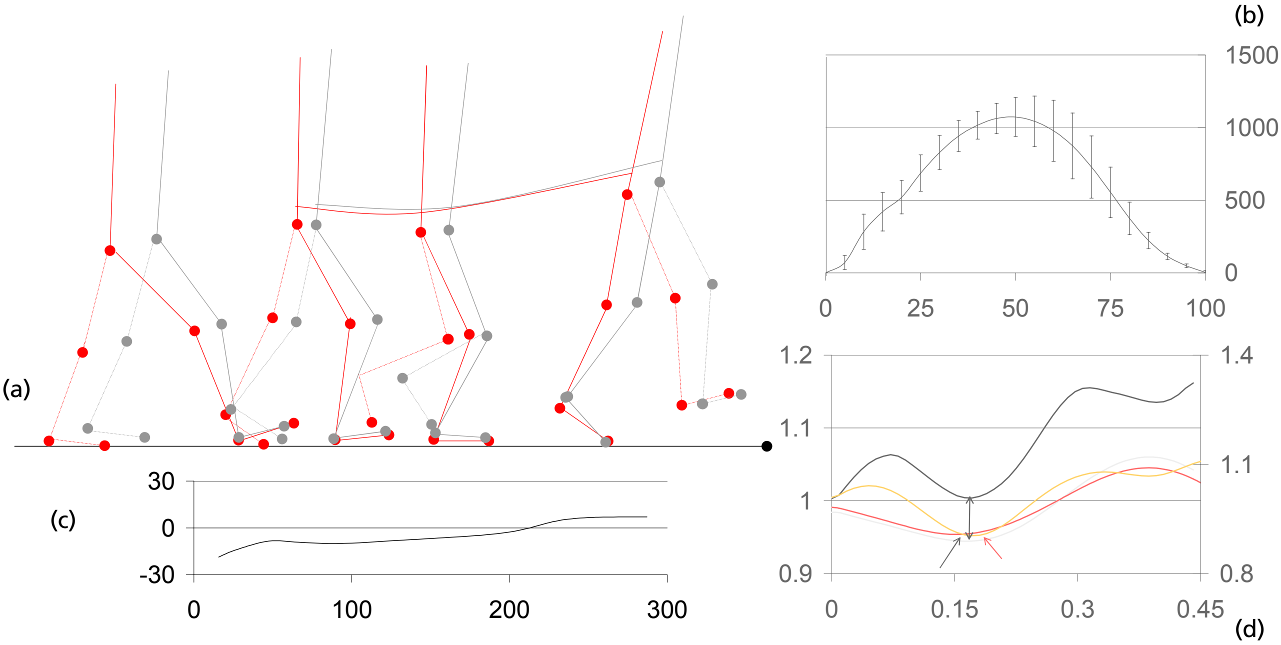

Figure 2. Kinematics, kinetics and dynamics of the WRT-step during overground and treadmill acceleration.

(a) Kinematics of *step 0* during overground (red) and treadmill (grey) acceleration at heel contact, toe-off contralateral foot, midstance and toe-off

(b) Vertical ground reaction force (N) of the transition step (normalized time axis)

(c) Centre-of-pressure during the transition step

- Horizontal axis = anterior displacement (cm)
- Vertical axis = mediolateral displacement COP (cm: negative = lateral; positive:= medial)

(d) Dynamics of the centre-of-mass during *step 0*

- Horizontal axis= time (s)
- Left Y-axis = gravitational potential energy (E_{pot}) normalized to mgh (h= height COM rest)
- Right X-axis = kinetic energy (E_{kin}) normalized to mv^2_{trans} (v_{trans} = transition speed)

Black and grey line represents Epot respectively Ekin during overground acceleration

Red and yellow line represents Epot respectively Ekin during treadmill acceleration

The effect of averaging data (over different acceleration ranges) is illustrated by comparing the trials of *one subject* performing WRT on a treadmill and overground at a similar acceleration (± 0.1 m s^{-2}). As can be seen in figure 3, the normalised movement pattern of foot, shank and thigh now do concur. The only remaining difference is the increase in trunk rotation that is smaller on the treadmill, which can be coupled to the use of a treadmill. Unconsciously the subjects might take into account that the treadmill will accelerate, whereas overground subjects have to generate their own acceleration.

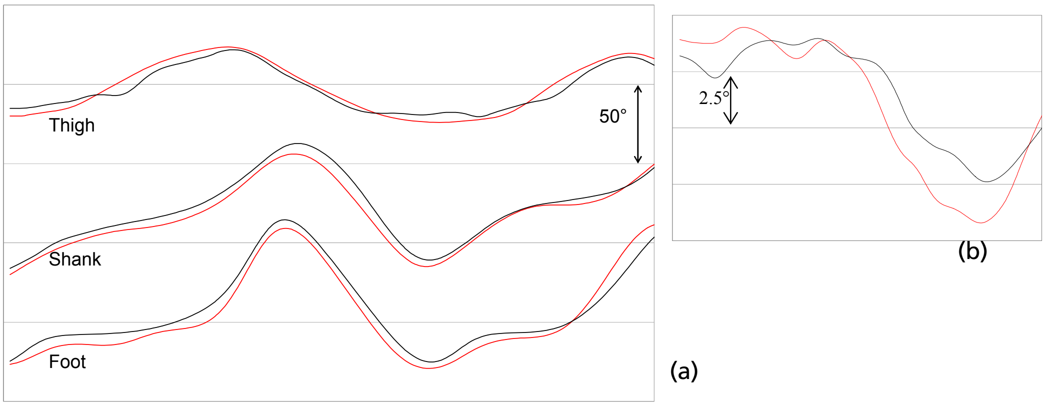

Figure 3. Segment angles in the interval from step-2 to step+1 for one subject (MB)

(a) foot, shank and thigh

(to represent all angles in one figure a constant was added to each segment angle, absolute values can be looked up in *Chapter 3*, the interval between grid lines in 50° for all angles)

(b) trunk inclination (anteversion/retroversion: interval between grid lines is 2.5°)

Red and black line represent the segment angles of the leg (standing leg during the transition step) and trunk during overground respectively treadmill acceleration across transition speed.

X-axis is a normalised time-axis (normalised to 100 points) starting at heel contact of step-2 ending at heel contact of step+1.

As mentioned before energy is invested to initiate the new running gait pattern. Reorientation of the trunk during the transition step leads to a sudden increase in forward velocity of the COM, accompanied by an increase in kinetic energy to set off the first floating phase. As can be seen in figure 2d, the energy jump is lower on a treadmill compared to overground. To seek out if averaging or acceleration here also can account for this observed difference, energy fluctuations were calculated for the same subject of figure 3. As can be seen in figure 4, averaging has a large impact on the energy jump as differences are no longer observed. Yet, the energy jump during overground acceleration appears more as a breaking point whereas during treadmill acceleration this energy jump occurs more gradually, which can be linked to the larger trunk rotation during *step 0* in the overground acceleration (Fig. 3b).

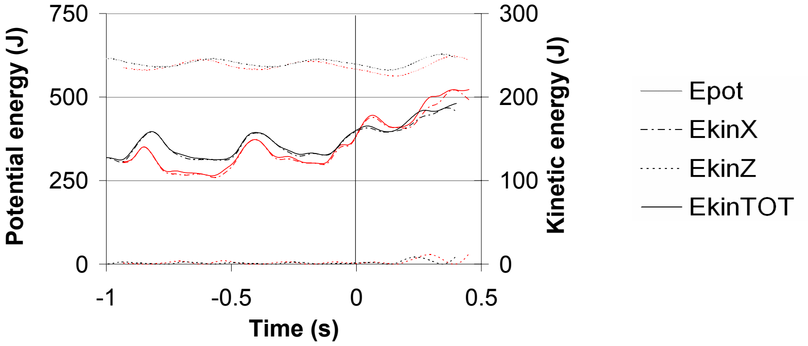

Figure 4. Comparison of energy fluctuations overground (red) and on a treadmill (black) with comparable average acceleration (± 0.1 m s^{-2}) of one subject (MB) in the interval step-2 to step+1.
The black line indicates the start of the transition step. Gravitational potential energy is graphed on the left axis, all kinetic energy components are graphed on the right axis.

Instantaneous COM power profiles presented in figure 5 confirm the above conclusions. Few differences exist between the power curves during overground and treadmill acceleration in proximity of the transition step. For running steps, negative COM power early in stance represents energy extracted from the system, either dissipated as heat or temporarily stored as elastic energy in tendinous structures. In the latter case, this energy can be recovered during the second part of stance when energy is added to the system again (positive COM power). For *step 0*, however, negative COM power levels during the first part of stance remains rather small in vertical direction compared to the following running steps (Fig. 5b). Consequently, the subsequent positive COM power peak (Fig. 5c) must be delivered to a large extent by concentric muscle activity.

The energy generated during *step 0* (see also *Chapter 4*) can be divided in three parts: one third needed to realize the constant acceleration, one third consumed by the trunk for reorientation and one third to initiate the first flight phase. The latter is likely delivered by the large leg extensors during the second half of stance (more initial flexion of the knee during *step 0* compared to following running steps).

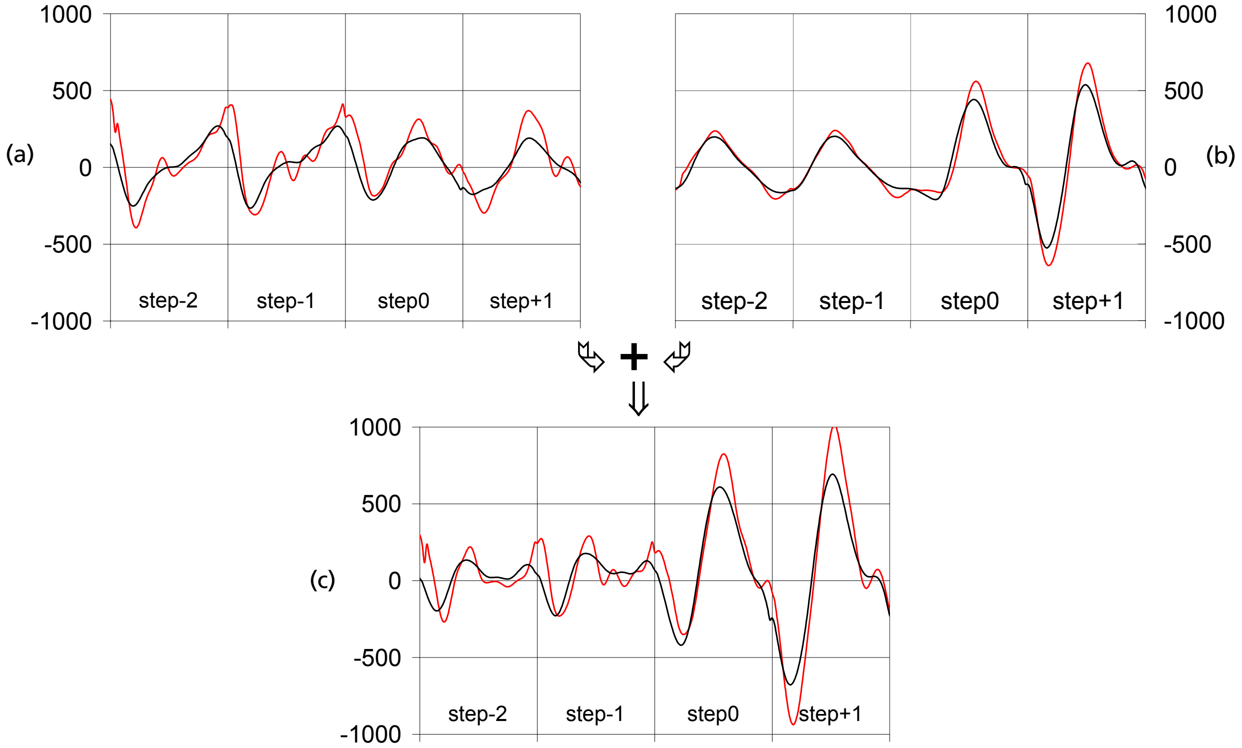

Figure 5. Power of the COM (Watt) during overground (red) and treadmill (black) acceleration (average)

(a) Horizontal power (Px)

(b) Vertical power (Pz)

(c) Total power (=Px+Pz)

It is important to acknowledge that accelerating on a treadmill and overground cannot fully concur, since there is no actual overall acceleration or deceleration in the global reference frame in the case of treadmill performance. Yet, given a treadmill acceleration of only 0.1 m s^{-2}, the missing inertial effect represent only a small fraction of the fore-aft forces (<5%). Simple modelling (see Appendix A) showed that the GRF-pattern experienced by the body when imposing such a small acceleration on the subjects, overground and treadmill conditions are practically indifferent, which is also reflected in the kinematical variables.

As has been shown in *Chapter 3*, a simple symmetry index offered a fourth way of detecting transition. Humans change from one to the other symmetrical gait pattern during the course of the WRT-step. The transition stride (with one walking leg and one running leg) is characterized by asymmetry, reflected in the spatio-temporal factors (step-1: duty factor= 0.56, *step 0*: duty factor= 0.46) and the kinematical variables (foot and shank). For example during step-1 and *step 0* in the WRT (one stride), the two legs do not perform the same actions. The trailing leg is walking (extension of the knee at midstance), the front leg is in the transition step with flexion of the knee at midstance. Thereby this asymmetry offers a useful tool to define transition and reminds of galloping, defined as a trailing walking leg and a leading running leg (Minetti, 1998, 2000; Whitall, 1989; Whitall and Caldwell, 1992; Whitall and Clark, 1994).

Thus, one might wonder if humans gallop through transition…

Taken into account that asymmetry is observed and the transition step is in se a galloping step, which is characterized by the dominant leg leading (Whitall, 1989), it seems plausible that humans prefer their dominant leg to realize WRT.

As can be seen in Table 2, the occurrence of transitions made with the dominant leg is dependent on the acceleration magnitude, intrinsic factors (local muscular fatigue of the TA), the environment (treadmill versus overground) and the condition (spontaneous versus imposed constant acceleration). As the task becomes harder (acceleration, fatigue, …) subjects prefer to make the transition with their dominant leg, which could be explained by the galloping character of the transition step. However, most likely this is related to the strength of the dominant leg that presumably delivers a part of the energy to start running (see above). If acceleration is coupled to the magnitude of the energy jump during *step 0* (as could be seen for one subject MB, Figs. 3 and 4), it seems logical that appearance of the dominant leg becomes more frequent when acceleration increases.

Despite this interesting laterality aspect, there remains –to my opinion– another intriguing question. As the transition step has the characteristics of a (semi-)galloping step, why is it that humans normally switch to running instead of going on in the galloping mode? Although galloping is energetically more costly than running, this seems not inconceivable. Since a considerable amount of energy is invested to realize the WRT, one might wonder what would happen if subjects are not (capable of) delivering this necessary energy jump. Would humans keep galloping in that condition, the way it is observed in young children when going faster (Minetti, 1998)?

WRT – dominant leg

Condition	*Acceleration*	*% dominant leg*		*Statistics* *df*	 *t*	 *p*
Treadmill	0.1	74 ± 15	**	12	5.572	.000
	0.07	50 ± 19		12	-.038	.971
	0.05	47 ± 19		12	-.646	.530
Treadmill fatigued	0.1	66 ± 18	**	12	3.167	.008
	0.07	61 ± 16	*	12	2.451	.032
	0.05	57 ± 19		12	1.144	.279
Overground	0.17	61 ± 11	*	8	3.254	.012
Overground	Spontaneous	65 ± 19	**	31	4.502	.000

Table 2. Transitions executed with dominant leg (*step 0* ~ dominant leg).

A one sample T-test was used to examine the difference of the percentage of transition executed with the dominant leg and 50 (no preference). * p<0.05 and ** p<0.01.

The dominant leg was determined using the questionnaire as presented by Coren in 1993. During the spontaneous overground transition, physical education students naïve to the purpose of the test were asked to accelerate at heir own pace and switch to running when it felt comfortable. This was recorded using video images, which were used to determine the transition step.

2. Preparation period

All examined parameters (spatio-temporal, kinematic, kinetic and COM) show a preparation in the approach of the WRT-step. Transition is suddenly realized but is prepared one or several steps (Fig. 6) before transition, depending on the variable (spatiotemporal parameters, COM, …) and the environment (treadmill/overground) in which transition is evoked.

Spatio-temporal factors (step length and step frequency) showed a non-linear preparation period of eight steps (Fig. 6a). Kinematic variables (shank, knee and trunk), on the other hand, showed changes during the last walking step(s) (step-2, step-1) leading to altered landing conditions at heel contact of *step 0* (Fig. 6b). The dynamics of the COM (Fig. 6c), vertical ground reaction forces (vGRF) (Fig. 6c) and the centre-of-pressure (COP) demonstrate different behaviour during the last step before transition.

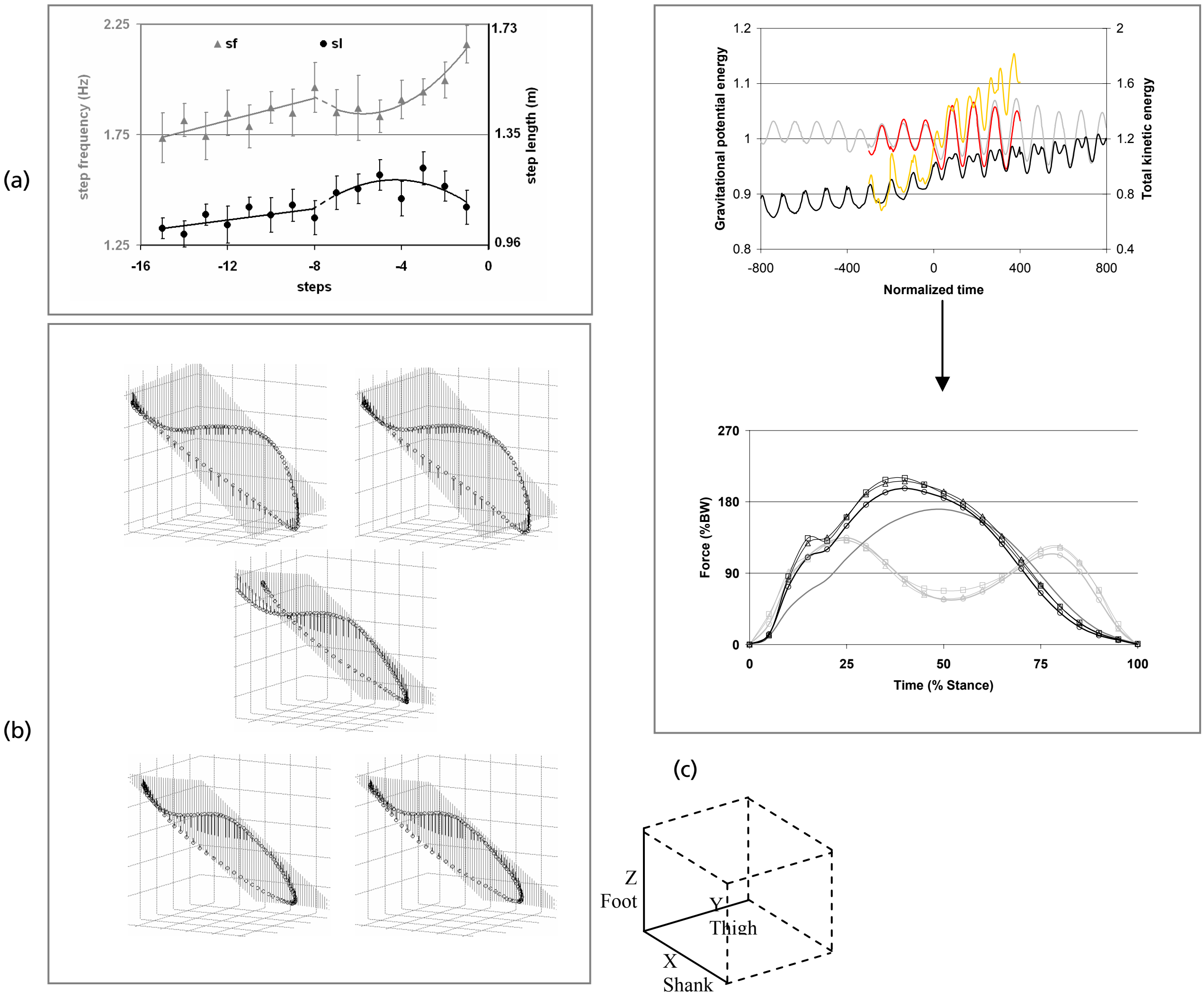

Figure 6. Preparation of the WRT

(a) Spatio-temporal characteristics from step-15 to *step 0* during treadmill acceleration (a= 0.1 m s^{-2}) (*Chapter 2)*

(b) 3D-kinematics during treadmill acceleration step-4 to step+4 (a= 0.1 m s^{-2}) (2D-graphs can be looked up in *Chapter 3*)

(c) Dynamics COM: gravitational potential (black and red for treadmill respectively overground acceleration) and total kinetic energy (grey and yellow for treadmill respectively overground acceleration). The dynamics of the COM reflected in the GRF pattern (*Chapter 3,4 and 5)*

How can this discrepancy regarding the duration of the transition process between different data sets be explained? Kinematic and kinetic variables showed differences during the last step(s) before transition. If we take a closer look at the spatio-temporal variables, step-2 and step-1 are clearly diverging from the previous walking steps, which is inherent to a polynome of the second order (deflection point) used to describe the relationship between step number and spatio-temporal variable. It could be that the highest R² values (used in chapter 2 to separate the linear from the second order polynome) do not accurately reflect whole body dynamics when approaching transition.

Another explanation could be that small non-significant adaptations of kinematic variables add one to another resulting in the non-linear evolution starting at step-8 of the spatiotemporal characteristics. The exact timing of the process, probably covering one or two steps, is –according to me- less important than the recognition of the preparation of the WRT. Most likely WRT is proximally prepared, leading to altered landing configurations initiating the actual realization of transition.

In conclusion the **WRT is mainly realized in the transition step**, characterized by a distinct kinematic, kinetic and spatio-temporal behaviour. It is, however, important to acknowledge that this transition was **prepared** during the last steps before transition: lower second GRF peak, changes in the step frequency- step length relation, **proximal** kinematical adaptations during the last stride before WRT-step leading to altered landing conditions, …

RUN-TO-WALK TRANSITION

The section on the RWT will be organised in the same manner as that on the WRT. However, as kinematics and dynamics of the COM were not obtained overground, some aspects cannot be examined. For example, RWT-speed was not assessed overground. A comparison of RWT-speed overground with treadmill is at this moment not possible.

1. Transition step

Decreasing speed from a comfortable running speed leads to a run-to-walk transition (RWT). RWT is mainly realized in one single transition step (Figs. 7 and 8). At the end of this step a double stance phase appears (spatio-temporal walking) and after an initial running start, the potential and kinetic energy components of the COM fluctuate out-of-phase (dynamical walking). More-over the standing leg occupies an intermediate position (between walking and running) and is clearly more extended compared to the previous running step (kinematical walking). The three ways (spatio-temporal, dynamical, kinematical) of defining the transition from running to walking concur during a deceleration across transition speed (Fig. 7).

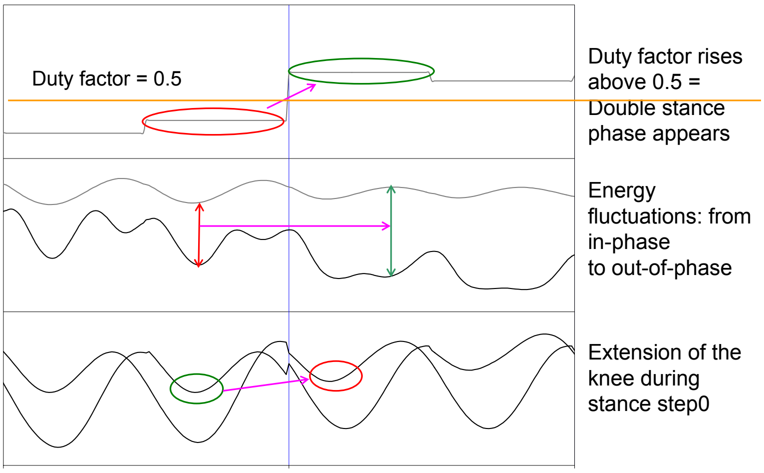

Figure 7. The three definitions of the RWT-step (Legend see Fig. 1)

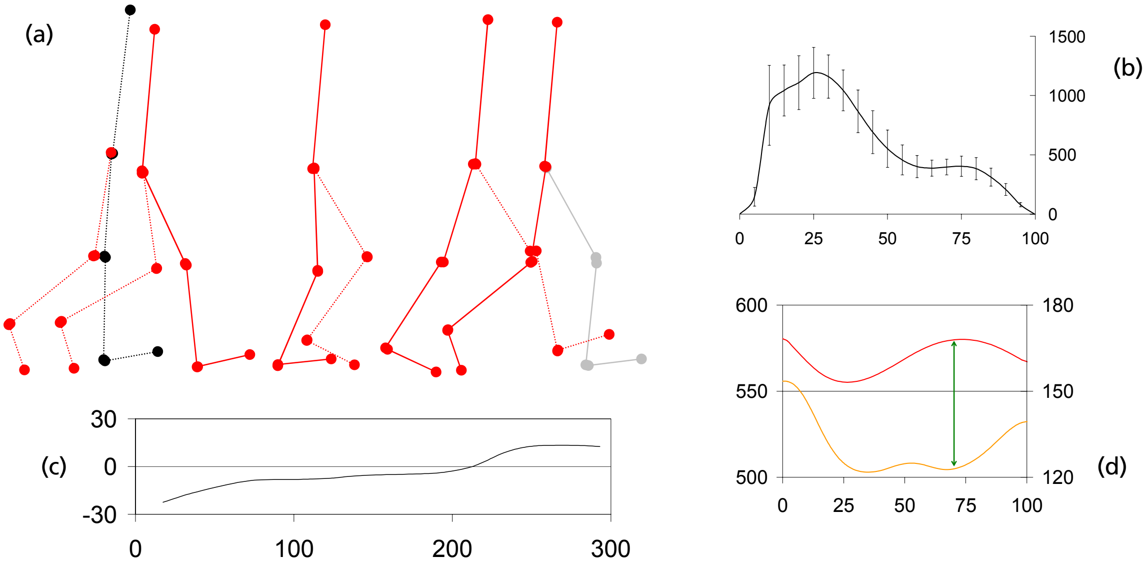

Figure 8. Kinematics, kinetics and dynamics of the RWT-step.

(a) Kinematics of *step 0* during treadmill deceleration (-0.1 m s^{-2}) at heel contact, toe-off contralateral foot, midstance and toe-off

(b) Vertical ground reaction force (N) of the transition step (normalized time axis)

(c) Centre-of-pressure during the transition step
  - Horizontal axis = anterior displacement (cm)
  - Vertical axis = mediolateral displacement COP (cm: negative = lateral; positive:= medial)

(d) Dynamics of the centre-of-mass during *step 0* (normalized time axis)
  - Horizontal axis= time (s)
  - Left Y-axis = gravitational potential energy (J): red line
  - Right X-axis = kinetic energy (J): yellow line

A fourth way of defining the transition zone was presented in *Chapter 3* by means of a simple symmetry index. Asymmetry was detected in the RWT-step starting with a flight phase and proceeding in the walking gait with a double stance at the end of *step 0*. Besides the spatio-temporal characteristics (one running leg and one walking leg), the energy profile of the RWT-step also reminds of the trailing leg during skipping (Minetti, 1998; Minetti, 2000). In the trailing skipping leg there is a potential concurrent energy transfer from vertical kinetic energy and potential energy to elastic storage and horizontal kinetic energy. Horizontal kinetic energy is used as an intermediate buffer and is later reused to load the front limb. In the RWT, a similar mechanism is probably applied. This horizontal kinetic energy, however, is used to reposition the trunk (retroversion of the trunk during *step 0* and step+1)

The remaining superfluous energy is most likely reduced by powerful energy absorption by the knee, which is also observed when humans stumble (Forner Cordero, 2003). Looking at the power profiles (Fig. 9), it is clear that energy is dissipated through the system during the transition step (negative power larger than positive power).

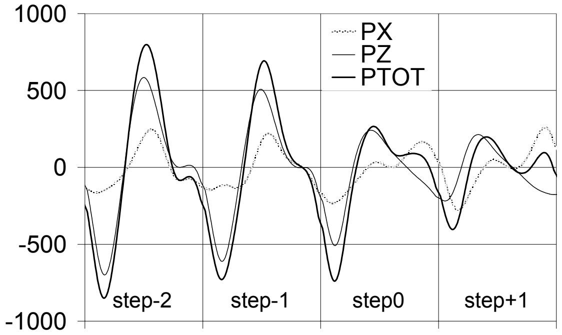

Figure 9. Power profile of the COM during the last running step (step-1), the RWT-step (*step 0*) and the first walking step (step+1) , calculated using the formula described in *Chapter 4*

During the WRT, we observed a preference for execution of the WRT-step with the dominant leg, which we coupled to the nature of the human gallop and to the energy that has to be generated to realize the WRT. In the RWT on the other hand, we do not need extra energy input to realize transition. Despite the fact that this mixed coordination pattern reminds of the gallop stride, we hypothesize that RWT will not be characterized by a larger number of RWT-steps with the dominant leg.

As can be seen in Table 3, no convincing supremacy of the number of RWT-steps with the dominant leg is present. This might be linked to the fact that RWT is actually only completed during the steps following the transition step. Dissipation of energy might take place during more than one step (probably two), which could be observed in the vGRF. This division of the RWT-task is also observed after perturbation of gait, where multiple steps are necessary to recover and stabilize the movement pattern. In the next paragraph we shall focus on these adaptations during the RWT-protocol.

RWT – dominant leg

Condition	*Deceleration*	*% dominant leg*	*Statistics* *df*	*t*	*p*
Treadmill	-0.1	52 ± 17	12	0.419	0.682
	-0.07	55 ± 22	12	0.833	0.424
	-0.05	46 ± 23	12	-0.525	0.610
Treadmill fatigued	-0.1	60 ± 15 *	12	2.426	0.031
	-0.07	50 ± 28	12	0.024	0.981
	-0.05	59 ± 18	12	1.791	0.101
Overground	± -0.17	48 ± 20	8	-0.803	0.578

Table 3. Percentage of RWT-steps with the dominant leg. Legend: see Table 2.

2. The adaptation period in the run-to-walk transition

A post-transition process or ‘post’paration during the first walking steps after the RWT-step was found for the spatio-temporal characteristics (Fig. 10a), kinematical variables (Fig. 10b) and vGRF (Fig. 10c). The spatio-temporal factors showed a non-linear evolution of 6 up to 8 steps after the transition step. But, only the first two walking steps show clearly different spatiotemporal behaviour (deflection point in the polynome of second order), which is in line with the duration found in the other biomechanical variables.

vGRF also showed changes in the last running step prior to the RWT-step (Fig. 10c). This could be due to sensitivity of the vGRF to subtle non-significant changes in the kinematical configuration. But, this difference could also be the consequence of (1) a functional difference in the realization of RWT on the treadmill (kinematics) versus overground (vGRF) or (2) the difference in the deceleration magnitude (-0.1 m s^{-2} on the treadmill versus -0.17 m s^{-2} overground). If subjects are imposed to a lower deceleration, preparation could be superfluous.

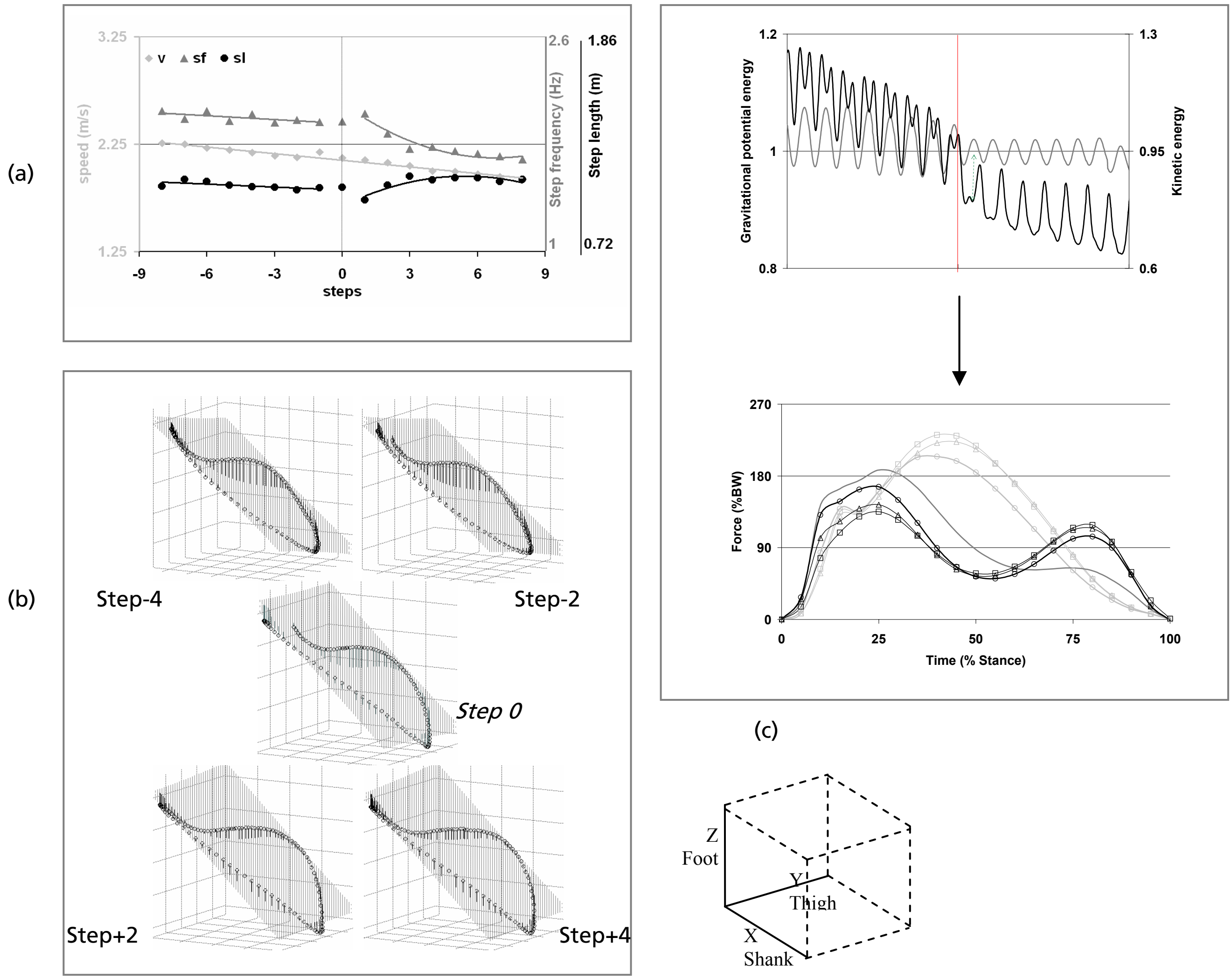

Figure 10. Adaptation during RWT

(a) Spatio-temporal characteristics from step -8 to step+8 during treadmill deceleration (a=-0.1 ms^{-2}) (*Chapter 2)*

(b) 3D-kinematics during treadmill acceleration step-4 to step+4 (a=- 0.1 m s^{-2}) (2D-graphs can be looked up in *Chapter 3*)

(c) Dynamics of the COM: gravitational potential (black) and total kinetic energy (grey). The dynamics of the COM reflected in the ground reaction force pattern (*Chapter 3, 4 and 5)*

In conclusion, **RWT is mainly realized during the transition step** but most likely a **'post'paration** (i.e. during the first walking steps) is necessary to adapt the system and to continue in a new stable gait pattern. Vertical GRF showed a preparation through a lower active peak, which probably facilitates the RWT-step in higher decelerations.

WRT VERSUS RWT

The spatio-temporal, dynamical and kinematical definition for transition between walking and running concur during WRT and RWT and indicate the same step as the transition step (Figs. 1 and 7). Although it concerns a very fundamental question and all definitions are alternatively applied in previous locomotion research, the concurrence of these definitions was never examined in proximity of transition. Despite the fact that this consensus is taken almost for granted, in the past other observations have been reported.

Humans are, for example, capable of walking according to the spatio-temporal definition with in-phase energy fluctuations, while running according to the dynamical definition. This phenomenon is better known as Groucho running (McMahon et al., 1987). After examining kinematics, vGRF and dynamics of the COM during actual acceleration and deceleration across transition speed, we conclude that adult women spontaneously avoid using that kind of locomotion in this type of protocol. This means that generating a flight phase goes hand in hand with the transition from out-of-phase to in-phase energy fluctuations, and vice versa for the occurrence of a double stance phase (Figs. 1 and 7). This concurrence is in contradiction to observations of spatiotemporal walking and dynamical running in spontaneous locomotion in elephants, some birds, crabs and primates (Rubenson, 2004, see also introduction).

Because WRT and RWT are both realized during the transition step and the walking steps in proximity of the transition step and the fact that WRT- and RWT- speed are equal, there might be a resemblance between both transitions (WRT and RWT).

WRT, on one hand, involves acceleration, hence an increase kinetic energy due to forward velocity. A RWT, on the other hand imposes deceleration and energy must be dissipated by the locomotor system. As can be seen in Table 4, the energy burst is simply reversed meaning that the energy input during the WRT-step equals the energy dissipation during the RWT-step. Despite this similarity, the actual realization of the transition step is different, which reinforced by the power profiles of the COM (Fig. 11). Power profiles of WRT- and RWT-step shows different dynamics indicating functional hysteresis, by which we mean that WRT and RWT are realized in different manners (see kinematics: Figs. 2a and 8a) and by other mechanisms.

WRT	**RWT**	**Paired sample T-test**		
Energy jump	*Energy loss*	*df*	*T*	*p*
33.78 ± 9.47	34.70 ± 13.20	12	-.202	.843

Table 4. Comparison of the energy jump and energy loss during WRT- respectively RWT-step
Paired sample T-test was used to compare absolute values of the difference in energy before and after transition.

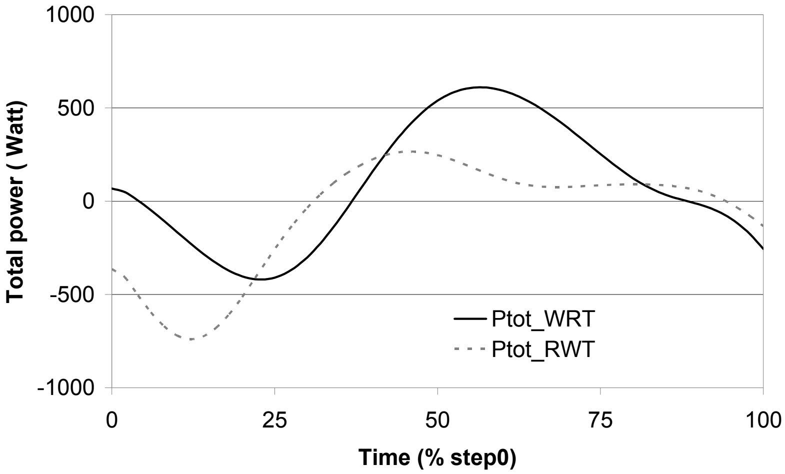

Figure 11. Comparison of the power during WRT- and RWT-step *(step 0)* on the treadmill

One of the reasons to study the transition phenomenon was to take a look at the collective output of the system to reveal aspects of the interplay between the fundamental neural and mechanical components of control. Before continuing on this matter, we return to figure 2 of the introduction (Fig. 12).

During human locomotion a simple drive descends from the higher brain stem to activate a central network or for locomotion central pattern generator (CPG) that transforms this simple drive into the coordinated activation pattern of many trunk and limb muscles. Functional movements appear from the interaction of these activation patterns and the intrinsic mechanical features of the locomotor system and environment and neural feedback. Taking the multitude of muscles involved into account (over 50 muscles in one leg) as well as the nearly endless number of possible interactions (other muscles and joints, gravity and other environmental factors, etc.), one probably gets an idea of the fascinating complexity the control system is dealing with in a simple daily-life task as walking, running or the transition between both.

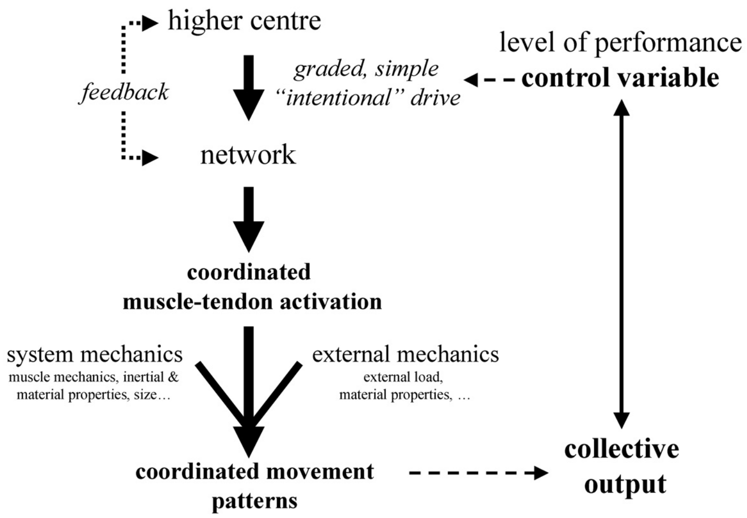

Figure 12. Simple representation of the control of human locomotion
(Personal conversation Prof. Dr. P. Aerts, also submitted to Journal of Integrative and Comparative Biology)

Despite the complexity and the vast number of possibilities, this results in a highly repeatable movement pattern, not only to generate forward progression but also to maintain balance, in the mean time limiting energy expenditure. All these tasks can be reflected in the behaviour of one virtual point, the centre-of-mass (COM) with only two degrees of freedom in the sagittal plane (anterior-posterior, up-down ward), not in the least affected by the organization of the lower limb segment angles. Since the study of the collective output (right side Fig. 12) allow obtaining insights in the organization of locomotion (left side Fig. 12), taking a look at the fluctuations of the COM and the segment angles that determine the position of the COM seems an obvious next step.

These segments are simply moved backward and forwards in an almost universal manner, as the same waveform pattern can also be observed in locomotion of the cat despite the obvious differences in posture and constitution (Lacquaniti et al., 1999). The pattern of the segment angles is only shaped in time and magnitude as a function of walking speed (Borghese et al., 1999). During walking, segments are organized in a planar covariation. This means that when plotting the orbit of segment angles (foot, shank, thigh plotted against each other) throughout one stride (cycle) this fits one single plane, thus reducing the degrees of freedom (Borghese et al., 1999; Grasso et al., 1999; Lacquaniti et al.,1999).

In this discussion, we chose to represent kinematics in 3d-plots, with one variable against the others. As can be seen in figures 6b and 10b, walking and running strides in WRT and RWT show a planar covariance, which is according to Borghese et al. (1999) an indication for a neural drive behind human locomotion and the transition between both modes of locomotion. The CPG launches motor commands to preserve kinematic invariance in locomotion (Borghese et al., 1998). This kinematic invariance is not an inherent feature of human motion as this is not observed in several voluntarily induced motions (for example kicking a ball, Lacquaniti, 1999).

It could be that if this kinematic invariance can no longer be guaranteed when increasing speed during WRT, the CPG moves at that specific speed (critical value) towards a new and more suitable planar configuration. This might explain why walking at speeds above the WRT-speed needs additional attentional resources (Abernethy, 2002). High speed walking has a need for higher brain centres overriding the characteristics of the CPG. This kind of reasoning also claims that differences in ground reaction forces are merely a by-product of the kinematic invariance that has to be aimed for.

Decreasing speed does not lead towards a deviation of the planar covariation (no kinematical adaptations before RWT) perhaps because RWT is not so compelling. It could be that previous experience (hypothesized by Thorstensson and Roberthson, 1987) induces subtle kinematic adaptations reflected in a decrease of the active peak in the last running step. A small short lasting (semi-) conscious adaptation during step-1 would lead to the quite different configuration of the RWT-step. This could explain the larger intra- and inter-variation and the fact that running below the RWT-speed does not need additional attentional resources (Abernethy, 2002).

PART 2. WHY DO HUMANS REALIZE GAIT TRANSITIONS?

IS THE M. TIBIALIS ANTERIOR REALLY IMPORTANT?

Part 2 starts with a brief summary of the existing literature on the trigger(s) of human gait transition. The next paragraph focuses on the influence of the m. tibialis anterior on human gait transition. First the kinesiology and biomechanical outcome is discussed followed by a small introduction in the neurophysiologic control behind muscle activation and locomotion.

1. Literature: one trigger or a pool of determinants

Perhaps, one of the most intriguing questions in transition research is why humans prefer to realize WRT and RWT at a speed below the energetically optimal transition speed. Transition research first looked for a causal factor explaining the occurrence of transition at that specific speed. Hreljac (1993) formulated four criteria in order to label a variable as trigger. The variable had to (1) change abruptly to a (2) different value at a (3) critical point that had to remain (4) constant in different conditions (Fig. 5, *Chapter 1*, p.18).

In literature many possible triggers have been proposed: muscular, energetic, optical flow, … (see introduction). So, it seems rather unlikely that human gait transitions would be caused by one single factor or trigger. Therefore, in the present research a pool of determinants (Fig. 6, *Chapter 1*, p. 19) was taken as a starting point. In normal circumstances the complex interaction of all these factors determines the normal locomotion pattern and the transition speed. In other words: Transition is the result of a multifaceted interaction of different stimuli (Daniels and Newell, 2003). Weakening one of the factors could give this factor a deterministic character or could influence the interrelation with other factors, driving the system via an instable configuration to another stable gait pattern.

It remains an interesting quest to find out all possible influencing factors of human gait transition as they give an idea of which factors shape human locomotion and how they accomplish this seemingly easy though very complex task (Farley and Ferris, 1998). Therefore, a second purpose of the present study was to unravel the controversial role of the m. tibialis anterior (Hreljac et al., 2001 versus Neptune and Sasaki, 2005).

2. The m. tibialis anterior and human gait transitions

2.1 Kinesiology

Before we continue on the relation between the m. tibialis anterior (TA) and human gait transition(s), the function of the TA during gait shall be described briefly. TA is concentrically activated at the end of stance, quickly rising the toes at toe-off. A second burst of activity is situated near heel contact where the TA is responsible for the preparation of heel contact through dorsiflexion of the foot and for positioning the foot in a controlled manner straight after heel contact (concentric-eccentric action) (Christina et al., 2001; Gefen, 2001; Perry, 1992). Because the secondary function of the TA is incersion, activity of the TA also restrains the subtalar joint during the heel rocker period (initial and forefoot contact phase: Gefen, 2001; Perry, 1992).

The TA has been proposed as a trigger by Hreljac (2001) and Prilutsky and Gregor (2001). In short, the small dorsiflexor would trigger the WRT in order to prevent local overexertion (Hampson et al., 2001; Mc Closkey et al., 1983) serving as a protective mechanism to prevent damage. Neptune and Sasaki (2005), on the other hand, argued for the importance of the plantar flexors and provided evidence for the non-significant role of the TA in the WRT.

In *Chapter 6*, we found that WRT-speed was lower after inducing local muscular fatigue in the TA whereas RWT-speed was not affected. This might indicate that TA becomes the weakest factor in the pool of WRT determinants and has an influence on the locomotor system. However, this does not necessarily mean that TA is the ‘trigger’ for the WRT.

Christina et al. (2001) showed that after localised muscular fatigue in the dorsiflexors the ‘desired’ foot angle at heel contact during running could no longer be reached, which was not found in the present study. There is tendency towards a lower retrograde position of the foot after fatigue but no significant differences were found (Table 5, *Chapter 6*, p. 155). Foot angle, however, is significantly lower (i.e. more antigrade) after the transition to running (*Chapter 3*, Fig. 2, p.83; *Chapter 6*, Table 5, p. 155). So, it could be that the TA is no longer capable of maintaining the more retrograde position of the foot during walking, thus lowering the WRT-speed.

The TA is relatively small mono-articular muscle and may not be strong enough to directly induce changes in the dynamics of the COM. The TA could however have a considerable effect on the interaction of the foot with the ground leading to changes in the COP. In fact comparing the foot unroll during walking and running, a faster forward displacement of the COP and higher medial velocity occur during ICP (initial contact phase) and FFCP (forefoot contact phase, De Cock et al., 2005). This could be a more comfortable task for the fatigued TA. After a more lateral placement of the foot (requiring little action of the TA), the controlled medial rotation of the foot during walking (requiring substantial action of the TA) can be avoided.

The description of the realization of WRT (part 1) variables reveals a proximal initiation of the WRT. Fatigue of the small distal mono-articular tibialis anterior muscle, on the other hand, influences WRT-speed (part 2). The answer for this ‘proximo-distal’ discrepancy could lie in the limited possibilities of the TA (mono-articular muscle), that is activated near its maximum capacity at the WRT. The larger muscles in the thigh and the muscles spanning the hip, on the contrary, have a large force delivering capacity, and are far from their maximal activation level. Consequently, they can handle much more demanding tasks than walking near transition speed (for example sprinting, high jumping, …).

Coupling fatigue of the TA to the ‘kinematic invariance’, as described at the end of the previous paragraph, this muscular fatigue might cause an altered position of the foot disturbing the planar covariance of the walking gait pattern, thus initiating the transition step in an attempt to maintain this feature of the CPG of human locomotion.

The proximo-distal discrepancy suggests that the proposition of more than one determinant or the pool of determinants is justified. ‘Fishing’ for all these determinants in the pool and revealing their inter-relationships seems important in future transition research (see also part3, future research). All possible influencing factors mentioned in the introduction (e.g. visual flow, m. gastrocnemius, …) should be incorporated in this light.

The RWT is not altered by muscular fatigue of the TA although one might expect that if TA would be the trigger for *‘the’* human gait transition, fatigue of the TA would postpone the RWT to avoid the uncomfortable area near transition speed. The fact that RWT is not altered supports the theory that WRT and RWT are two different phenomena. WRT and RWT are not only realized differently but also are determined by other factors. Although WRT and RWT are two inextricably bounded phenomena, both transitions should be studied separately. We do not suggest uncoupling WRT and RWT but we want to emphasize the different mechanisms behind both transitions.

2.2. Neuromotor steering

Increasing speed of locomotion is characterized by a progressive increase in heart rate, blood pressure and muscle nerve sympathetic activity (Fisher and White, 2004). This pressor response is controlled by central and peripheral mechanisms. The muscles need more oxygen and the body acts upon this need. There are three neural control mechanisms contributing to the cardiovascular responses to exercise: the central command, the arterial baroreflex and the exercise pressor reflex (Darques et al., 1998; Fisher and White, 2004; Joyner, 2005; Smith et al., 2006; Turner, 1991; Williamson et al., 2006).

The **central command** (Fig. 13) is a mechanism, which arises from higher centres of the brain. The latter sends out signals to activate cardiovascular control areas in the brainstem by which means the sympathetic and parasympathetic activity are modulated. These autonomic adjustments elicit changes in heart rate and blood pressure proportional to the intensity of exercise and act as a feedforward controller of the cardiovascular system (Fisher and

White, 2004; Joyner, 2005; Smith et al., 2006; Turner, 1991; Williamson et al., 2006). A second mechanism is the **arterial baroreflex** (Fig. 13) that regulates blood pressure on a beat-to-beat basis. Therefore, afferent fibres originating in carotic sinus and aortic arch adjust heart rate, stroke volume and peripheral resistance (Joyner, 2005; Smith et al., 2006; Williamson et al., 2006). Third, the **exercise pressor reflex** is a peripheral neural drive stemming from the skeletal muscle. This feedback from the contracting muscle evokes a raise in blood pressures and to lesser extent an increase in heart rate and ventilation. These exercise induced signals are generated by the group III (predominantly mechanically sensitive) and group IV (predominantly metabolically sensitive) muscle afferents (Adreani et al., 1997; Fisher and White, 2004; Joyner, 2005; Smith et al., 2006; Turner, 1991; Williamson et al., 2006).

Due to the increase in speed, step length and step frequency increase. Furthermore, more muscle activity is needed to maintain the increasing movement velocity. Consequently oxygen supply increases and lactic acid and other metabolites are produced. This leads to an increased stimulation of type III (mechanoreceptors) and IV (metaboreceptors) afferents. The latter also act upon painful stimuli, fatigue and overexertion and are, therefore, also called nociceptors. This combined feedback (type III and IV afferents) assists in tuning the cardiovascular and muscle activity.

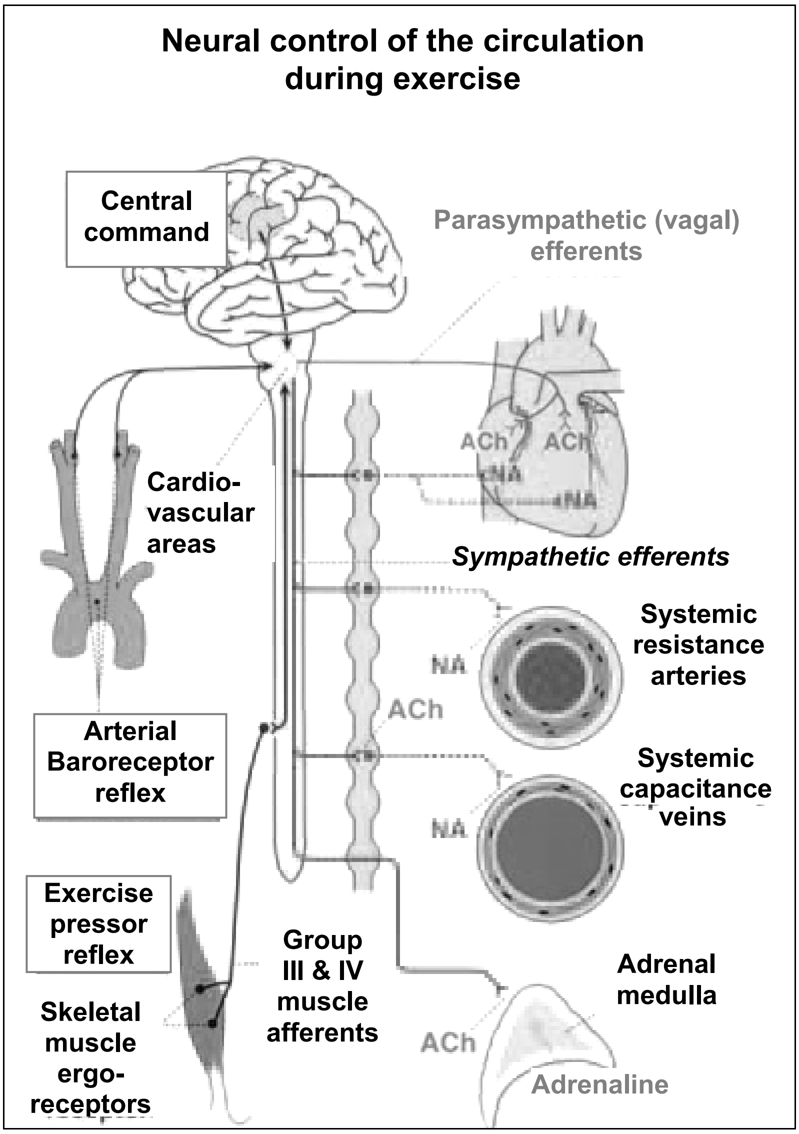

Figure 13. Neural cardiovascular control during exercise *(Smith et al., 2006, p.90).*
Neural signals originating from the brain (central command), the aorta and carotid arteries (arterial baroreflex), and skeletal muscle (exercise pressor reflex) are known to modulate sympathetic and parasympathetic nerve activity during exercise.
ACh, acetylcholine; NA, noradrenaline

Relating this to the TA and gait transitions, it could be that the TA indeed produces a signal capted by the type IV afferents alerting the central pattern generator, motorneuron and central command (Fig. 14, Zehr et al., 2004). This could be the introduction of gait transition: it just happens? After fatigue type IV afferents are activated more (Darques et al., 1998; Gandevia, 2001), which might explain the lower WRT-speed.

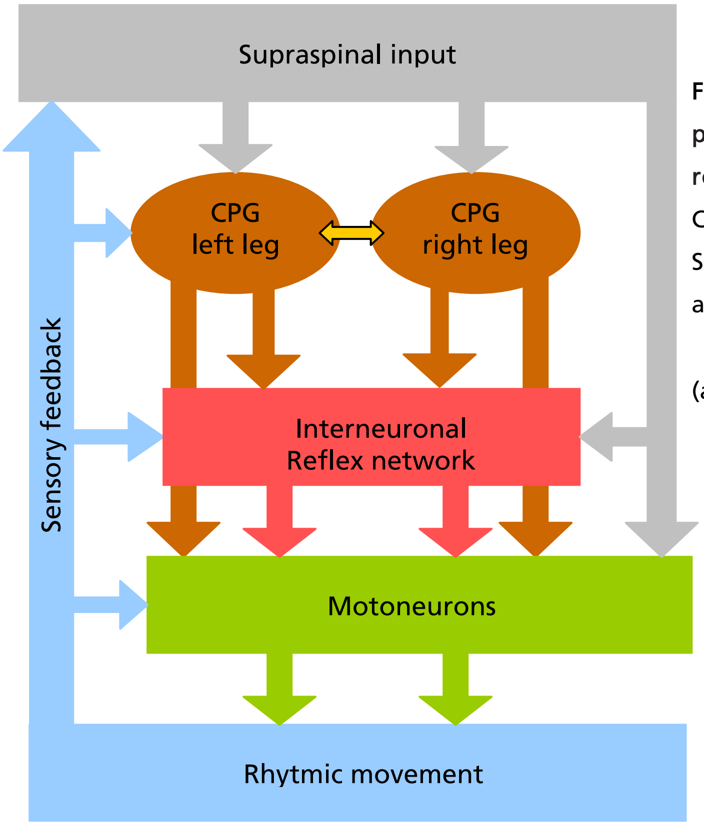

Figure 14. Schematic illustration of the possible organization of neural mechanisms regulating rhythmic movement.

CPG = central pattern generator

Sensory feedback: type III and IV muscle afferents

(adapted from *Zehr et al., 2004*)

Although we do not have the expertise and knowledge on how to check this hypothesis, this can contribute significantly to the knowledge of how muscle afferents affect the motor modulation.

PART 3. SHORT-COMINGS IN THE PRESENT RESEARCH

&

WHAT THE FUTURE SHOULD BRING …

LIMITATIONS AND SHORT-COMINGS OF THE PRESENT RESEARCH

Some limitations were already mentioned in the articles (*Chapter 2-6*). But after four years and during the course of the writing process of the dissertation, a researcher usually gets wiser, more practically oriented and looks at each research method with the data handling in the back of the mind. This section will, therefore, be written as:

'If I would start all over again, then I would…'

(1) ... study kinematics at different accelerations on a treadmill.

One of the limitations of the present research is the lack of kinematical data of WRT and RWT on a treadmill using different accelerations, as was the case for the spatiotemporal data. This would allow for the calculation of the energy-burst (*Chapter 4*) in different conditions within the same population and in the same environment. With the current evolutions in gait analysis methodology the number of markers can be diminished, the capturing of three-dimensional kinematical markers using infra-red cameras is improved and a semi-automatical processing of markers is in development, even if the researchers apply a whole human body model with over 60 markers.

(2) ... match the overground to the treadmill acceleration.

Accelerating overground was new and very challenging. Although subjects followed a constantly accelerating running light in order to reach the same accelerations compared to the treadmill, the overground acceleration did not match well with the acceleration imposed to the subjects accelerating on the treadmill. Similar accelerations could have facilitated the comparison between both and might have added insight in the difference between both.

(3) ... calculate joint moments and powers.

Joint moments represent the sum of the forces developed by muscles and other structures crossing the joint (ligaments, tendons, cartilage, …). Joint power summarizes the vital role of muscles during movement: the muscle's function as it shortens or lengthens under tension. (Winter, 1984; Zajac et al., 2002). Therefore, joint moments and powers would have provided extra insights. However, technical problems caused failure in the synchronisation of ground reaction force measurements and three-dimensional kinematical recordings (horizontal GRF's were not recorded either), which made it impossible to calculate joint moments and powers.

(4) ... compare ground reaction forces of an overground and treadmill acceleration

As mentioned in the discussion, overground and treadmill acceleration can not fully concur, since there is no actual overall acceleration or deceleration in the global reference frame in the case of treadmill performance. Therefore, it seems interesting to study differences of these kinds of accelerations (used in this dissertation thesis) on the level of ground reaction forces using an instrumented treadmill on one hand and a walkway with multiple force plates imbedded on the other hand. An absolute prerequisite in this comparison is a comparable acceleration magnitude.

THE FUTURE IN TRANSITION RESEARCH THROUGH ROSE-COLOURED GLASSES

Taken the present results in account, the author will give suggestions for further research on human gait transitions.

(1) Study the dynamics of the COM during RWT

Due to time constraints, kinematics and consequently the dynamics of the COM of the overground deceleration (RWT) were not processed. Because the ground reaction forces indicated differences in the last step before transition, one might wonder if this difference can be translated to kinematics.

(2) 'Fishing' in the pool of (sub)determinants

According to our opinion, the steering mechanism behind transition can be explained using three different models. In the *hierarchic model* one specific determinant dominates all other determinants from the pool. By example: it is not inconceivable that the characteristics of the inverted pendulum determine the WRT. The pendulum is not pushed to the limit (Froude-number 1 at ± 3m s^{-1}), but is not effective anymore at transition speed. Besides this, subdeterminants can override the global mechanism of the inverted pendulum. Second, the *threshold-model* implies that transition occurs when a determinant, no matter which, reaches its critical value and gives rise to transition, independent of the status of all other (sub)determinants. Third, the *context-model* assumes that transition is the result of a complex interaction between several determinants and by that means determined by the specific conditions in which transition occurs (treadmill/overground, optical flow, fatigue m. tibialis anterior, …).

In chapter 6, fatigue was induced in the TA and was found to influence the WRT-speed. At first thought, it seems interesting to take a look at the effect of strengthening the TA. Doing so, though, could influence other related factors or could push the TA away from the weakest link in the chain. More-over, Hreljac and Ferber (1995) were not able to find a correlation between absolute strength of the dorsiflexors and the transition speed. Currently, P. Malcolm, a researcher of our laboratory, is using recent technologies to assist the muscle at specific points in the step cycle to examine the role of the dorsiflexors and plantar flexors more closely.

In order to unravel the aspects of why humans change their gait pattern, it could be interesting to examine multiple determinants (see supra). By that means the hierarchy or interaction between possible determinants could be investigated. For example, optical flow and tibialis anterior are two clearly independent factors in the pool of WRT determinants (Hreljac et al., 2001; Mohler et al., 2004; Segers et al., accepted). The study of the influence of optical flow on human gait transition is recently started up by K. De Smet, another member of our transition locomotion research unit.

Antrophometry and morphology are possible candidates in the explanation of interindiviual differences in human giat transition speed. Age and gender were controlled for in the present study. Gender probably does not affect gait transition speed (Hreljac, 1995). Age, however, most likely does influence gait transition speed, as it also has clear influence on preferred walking and running speed (Bus, 2003; Dusing and Thorpe, in press; Hallemans, 2005; Menz et al., 2004; Schepens et al., 1998). Toddlers walk, but only at the age of seven a mature gait pattern is developed (Hallemans et al., 2005). Even then, with maturation and growth, preferred walking and running speed increase. The latter is alo reflected in an increase in human gait transition when comparing 11 year olds to 15 year olds (Tseh et al., 2003). During adolescence and adulthood human gait transition speed most likely remains constant. Afterwards, in older people (> 55 years) ageing causes a decerase in preferred walking and running speed (Bus, 2005; Menz et al., 2004). It remains unknown whether or not this influences gait transition speed, but following the same line as in childhood we think that human gait transition speed decreases. Therefore, it could be extremely appealing to examine gait transition over life, especially during the first years of independent walking and running and in older people.

(3) Modelling

In the WRT we observed altered landing conditions at heel contact of the transition step as a result of preparation of the swing leg during the last walking step. Therefore, it seems plausible that WRT is nothing more than an effect of the altered landing conditions. It could be the latter activate a simple reflex loop flexing the stance limb.

Subsequently the trunk is moved forward delivering the necessary energy to initiate the running gait pattern. Therefore it seems interesting to model the swinging leg and examine the influence of different configurations during swing on the landing configuration and the subsequent reaction during the following step. In the general discussion, I argued that insufficient energy delivery might result in a sustained galloping. By modelling the swing leg and the stance limb, variation of energy input is possible enabling the examination of this hypothesis.

(4) Kinematic invariance

Kinematic invariance appeared as an important task constraint for the central pattern generator (CPG). Perhaps changes in the transition speed could be induced by disturbance of the normal locomotion pattern, thus altering the planar covariation and perhaps change transition speed.

(5) Joint moments and powers

As mentioned above, one of the limitations of the present study was the inability to calculate joint moments and powers during actual acceleration and deceleration across transition speed. Repeating the present protocol of overground acceleration might address this lacuna. More-over by implementing different accelerations during the overground acceleration (similar to acceleration on the treadmill), a valid comparison with treadmill data could be accomplished.

(6) Spontaneous transitions

In first instance, we applied the ecological more valid ramped protocol instead of the accepted stepped protocol on a treadmill. To create an even more ecological valid environment, we simulated a constant acceleration overground. To take it even one step further, it might be interesting to take a look at spontaneous accelerations. We did a small pretest during which subjects were asked to accelerate at their own pace and change to the running gait whenever it felt natural. One of the most remarkable observations (qualitative) is the sudden speed jump during the transition step. Once the spontaneous speed pattern in approach to transition is known, it would be very interesting to impose this kind of acceleration on the subjects using an instrumented treadmill.

In the same line, Minetti (1994) and Saibene and Minetti (2003) suggested that transition speed is an artificial concept and that humans would jump to a higher speed at WRT during spontaneous daily life acceleration. Therefore, it would be extremely appealing to take a deeper look at these everyday transitions. For example: I’m walking, I see the bus and I immediately start running. There are several aspects that still needs research as this an unexploited area of locomotion research. Using the insights gained in this thesis might help understanding the spontaneous daily life transition. The laterality aspect as observed might be more dominant during this transition as such a transition needs a sudden rapid high acceleration. Would subjects prefer their dominant leg and seek to realize the transition with the dominant leg? What is the reaction time for subjects to initiate the transition? Is this dependent on the foot placement? There are a lot of questions, but no available answers.

I have discovered some facts and relationships that others can now disprove.

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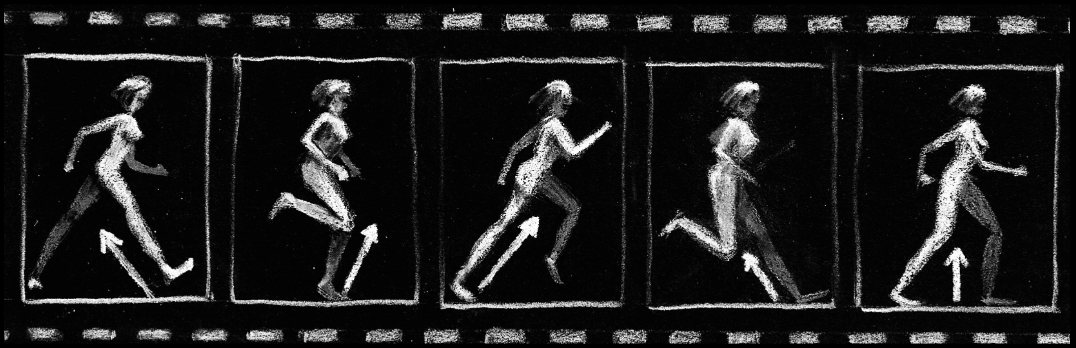
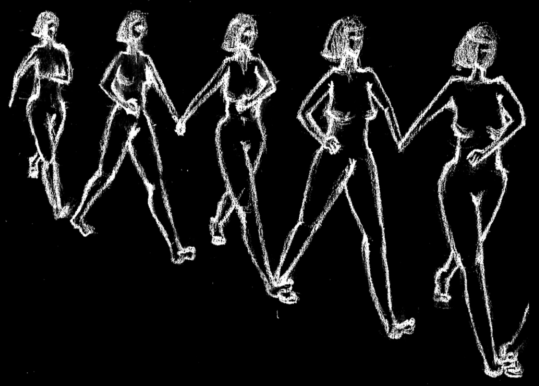


Chapter 8

Summary

Samenvatting



SUMMARY

BACKGROUND

To move from one place to another, humans walk at lower speeds and run when they are in a hurry. To increase their speed, humans switch from walking to running at a specific speed (walk-to-run transition = WRT). On the contrary, when running and willing to decrease speed, a run-to-walk transition (RWT) obtrudes itself at a certain instant. Human gait transitions are peculiar phenomena as the WRT-speed is well below the maximal walking speed and the RWT occurs although humans can run at speeds below the RWT-speed. More-over, neither one of these transition is realized at the energetically optimal transition speed. Taking into account that the understanding of the transition between walking and running may offer insight in the key factors that shape human locomotion, the answer on why humans change their gait pattern at that specific speed, becomes even more appealing. In literature, many possible triggers for eliciting such transition have been proposed (muscular, energetic, optical flow, etc.). Therefore, it seems doubtful that transition would be triggered by one single factor or trigger. Instead, a pool of determinants was proposed, in which the weakest factor and its interrelations will provoke transition. Despite the fact that knowledge of the actual realization of transition (how?) could enhance the global vision on transition, few studies addressed this matter to date.

PURPOSE

The main purpose of the present study is to take a deeper look at the transition step(s) during actual acceleration or deceleration across transition speed (*How*?). A second purpose is to verify the theory of a pool of determinants by weakening one of the possible triggers (*Why*?).

METHODS

Four aspects of the actual realization of gait transitions are examined; spatio-temporal variables, kinematics, dynamics of the body centre-of-mass (COM) and external forces. Spatio-temporal and kinematic variables are examined on a constantly accelerating (WRT) or decelerating (RWT) treadmill. Dynamics of the COM and kinetics are studied overground, where subjects were instructed to follow a constantly accelerating light.

All these aspects are studied in a broad range of steps around the transition step, the first step with a flight or double stance phase during WRT respectively RWT. This broad range allows for the detection of a possible preparation strategy in approach to the transition step and perhaps the adaptation after the transition step to continue locomotion in the new stable mode of locomotion. In all studies a homogeneous population (active females, height being minimal 1.65 and maximal 1.75) is chosen to minimize influence of anthropometry.

RESULTS

The first study focussed on the spatio-temporal variables around the transition step, as they are fundamental biomechanical parameters reflecting the organizational status of the locomotor system. We found that WRT- and RWT-speed do not differ for all imposed accelerations (0.05, 0.07, 0.1 m s^{-2}). The WRT-step shows unique 'transitional' spatio-temporal characteristics and is 'pre'pared during the last walking steps. The RWT-step is followed by a post-transition period, i.e. during the first walking steps, to complete the actual realization of transition and continue in the stable walking gait pattern.

In a second study, kinematics of human gait transition were examined as this allows to get a clear view on the actual realization of the transition. The transition step in WRT and RWT is a kinematic outlier, in which the main changes from one gait pattern to another are realized. Despite this sudden change, a transition process also appears in both transitions. In the WRT, transition is 'pre'pared and kinematic adaptations are found in the last swing before transition eliciting altered landing conditions. RWT is 'post'pared and only completed after a reorientation of the trunk that was accomplished during the first walking stride after transition. Furthermore, a functional interlimb asymmetry is recognized as a unique characteristic of the transition stride, offering a practical way of identifying the transition.

A third study focussed on the energy fluctuations of the body centre-of-mass (COM). When walking, potential and kinetic energy fluctuate out-of-phase and a considerable amount of energy is recovered in a pendulum-like fashion. In contrast, running involves in-phase fluctuations of the mechanical energy components of the COM, allowing elastic energy recovery only. In order to obtain an idea of how humans switch from out-of-phase to in-phase energy fluctuations, dynamics of the COM are studied during overground acceleration across WRT-speed. Humans realize this WRT abruptly in one single step. In this transition step mechanical energy is actively generated to launch the body in the floating phase of the first running step and to bring the trunk in its more inclined orientation during running. As a result, the pendular energy transduction drastically decreases in this step. The system immediately proceeds with the typical in-phase fluctuations of kinetic and potential energy.

The fourth study examined the ground reaction force (GRF) to improve the comprehension of gait transitions. The GRF is the only external contact force in gait and reflects the dynamics of the locomotor system during stance. The transition step (WRT and RWT) is characterized by an outlying pattern of the vertical GRF (vGRF) and trajectory of the centre-of pressure (COP), i.e. the point of application of the GRF vector. In the WRT, transition is, again, ‘pre’pared and kinetic adaptations are found in the last step before transition, namely a smaller second vGRF-peak and a faster forward displacement of the COP. RWT is ‘pre’- and ‘post’pared and only completed during the first walking step. While ‘pre’paration exists of a smaller active peak in the vGRF during the last running step, ‘post’paration is characterized by a larger first peak in the vGRF during the first walking step.

The purpose of the last study was to investigate the hypothesis of a pool of determinants. By fatiguing the tibialis anterior muscle (TA), i.e. weakening one of the proposed triggers, an altered transition speed was expected. Indeed, WRT-speed is lower after inducing muscular fatigue in this small dorsiflexor. RWT-speed on the other hand is not influenced. This confirms that the TA is likely one of the determinants in the pool of the WRT, and that WRT and RWT are probably determined by other variables.

CONCLUSIONS

Realization of the actual WRT and RWT, when gradually changing speed, is mainly realized in one transition step, characterized by specific ‘transitional’ spatiotemporal, kinematic and kinetic features. Despite this abrupt change, during WRT and RWT transition related adaptations are found within the steps in proximity of the transition step. All studied variables argue for ‘pre’paration of the WRT during the last walking steps before transition. RWT seems rather ‘post’pared as adaptations occur predominantly during the first walking steps after the transition step, which allow continuing the new stable walking pattern.

Most likely, WRT and RWT are not solely determined by one factor but by a pool of determinants. Not only fundamental differences between WRT and RWT were found in the realization but indications for different determinants of both transitions as well.

A noteworthy finding is that the three most commonly applied definitions of the transition between walking and running concurred, even in proximity of the transition step. During walking, out-of-phase fluctuations of energy (dynamical definition) go hand in hand with the presence of a double stance phase (spatio-temporal definition) and a more or less extended stance limb (kinematical definition). In-phase fluctuations of energy during running are accompanied by the presence of a flight phase and flexion of the stance limb.

SAMENVATTING

ACHTERGROND

Om zich te verplaatsen, kan de mens beroep doen op verschillende wijzen van voortbewegen. Als hij zich traag beweegt, wandelt hij. Als hij gehaast is, loopt hij. Wanneer hij sneller begint te wandelen, schakelt de mens op een bepaald moment over van wandelen naar lopen (wandel-loop transitie = WRT). Wanneer hij trager gaat lopen, schakelt hij op een bepaald moment over van lopen naar wandelen (loop-wandel transitie = RWT). Deze overgangen (gangtransities) zijn des te opmerkelijker aangezien ze spontaan plaatsvinden op een welbepaalde snelheid zonder dat het echt noodzakelijk is. De mens kan zowel sneller wandelen dan de WRT-snelheid (± 7.2 km h^{-1}) als trager lopen dan de RWT-snelheid (tevens ± 7.2 km h^{-1}). Bovendien worden noch de WRT noch de RWT gerealiseerd bij de energetisch optimale transitiesnelheid. Het antwoord op de vraag waarom de mens kiest voor die specifieke overgangssnelheid is niet alleen leerrijk en interessant, maar het begrijpen ervan kan ook leiden tot een beter inzicht in de voornaamste factoren van de menselijke locomotie.

In de bestaande literatuur worden er voor het tot stand komen van zo’n overgang verschillende factoren als determinant voorgesteld. De transitie zou kunnen voortvloeien uit elementen van musculaire, energetische, visuele, e.a. aard. Het lijkt dus onwaarschijnlijk dat gangtransities veroorzaakt zouden worden door één welbepaalde determinant. Daarom werd een ‘pool van determinanten’ voorgesteld waarin de zwakste schakel en zijn onderlinge verbanden de overgang zouden uitlokken. Tot op heden is weinig onderzoek verricht naar hoe transities tot stand komen ondanks het feit dat dit verhelderend zou kunnen zijn voor de totale visie op transitie en dit de zoektocht naar de determinanten in de pool zou kunnen sturen. Daarom dient er verder onderzoek te worden verricht naar deze materie.

DOELSTELLINGEN

Het voornaamste doel van dit proefschrift is dieper in te gaan op het transitieproces tijdens een versnelling of vertraging, waarbij de nadruk werd gelegd op de kenmerken van de realisatie van zowel de overgang van wandelen naar lopen als die van lopen naar wandelen (*Hoe*?). Een tweede doel is de voorgestelde theorie van de pool der determinanten te testen op hun bijdrage bij transities (*Waarom*?).

METHODE

Vier aspecten van de eigenlijke realisatie van gangtransities werden onderzocht: spatio-temporele factoren (staplengte, stapfrequentie, dubbele steunfase …), kinematische variabelen (kniehoek, enkelhoek …), de dynamica van het lichaamszwaartepunt (verticale en horizontale verplaatsing, energiefluctuaties, …) en de externe krachten die inwerken op het systeem (grondreactiekrachten en drukcentrum). Spatio-temporele en kinematische variabelen werden onderzocht op een loopband die werd opgedreven met een constante versnelling. Dynamica van het lichaamszwaartepunt (COM) en kinetische variabelen werden bestudeerd op een loopweg, waarbij de subjecten gevraagd werden een rij oplichtende lampjes te volgen. Doordat de lampjes met constante versnelling opflikkerden, nam de snelheid van de proefpersonen toe met een bij benadering constante versnelling.

Al deze aspecten werden bestudeerd tijdens en rond de transitiepas, gedefinieerd als de eerste pas met een vluchtfase in de WRT en de eerste pas met een dubbele steunfase in de RWT. Het onderzoeken van een aantal passen voor en na de transitiepas laat toe na te gaan of transitie een plots discreet gebeuren is of eerder een proces gespreid over enkele passen waarin aanpassingen gebeuren om het lichaam ofwel voor te bereiden op de transitie of om deze transitie te vervolmaken tijdens de eerste passen na transitie.

In alle studies werd geopteerd voor een homogene populatie van fysiek actieve vrouwen met een welbepaalde lichaamslengte (tussen 1.65m en 1.75m) om de invloed van antropometrische kenmerken op de resultaten te minimaliseren.

RESULTATEN

In een eerste onderzoek werden spatio-temporele variabelen van naderbij bekeken omdat deze fundamentele biomechanische parameters zijn die de organisatie van het lichaam weerspiegelen. Ondanks het gebruik van verschillende versnellingen / vertragingen (0.05, 0.07, 0.1 m s^{-2}) worden geen verschillen in transitiesnelheid gevonden tussen WRT en RWT (7.8 km h^{-1}). De transitiepas in de WRT wordt gekenmerkt door specifieke afwijkende ruimtelijke en temporele factoren. Bovendien zien we dat de WRT wordt voorbereid tijdens de laatste wandelpassen voor de transitiepas. In de RWT daarentegen, merken we een adaptatieperiode op na de transitiepas om uiteindelijk een stabiel wandelpatroon te bekomen.

In een tweede onderzoek werden de kinematische variabelen bestudeerd omdat deze het mogelijk maken een beeld te krijgen van het eigenlijke bewegingspatroon in aanloop naar, tijdens en na de eigenlijke transitiepas. Transitie, zowel in de WRT als in de RWT, wordt voornamelijk gerealiseerd tijdens de transitiepas die dan ook wordt getypeerd door een bewegingspatroon dat afwijkt van zowel wandelen als lopen. Ondanks deze plotse transitie, zijn eveneens kinematische veranderingen (aanpassingen) waarneembaar. Net zoals in de eerste studie zien we een voorbereiding van de WRT die plaatsvindt tijdens de laatste zwaaifase wat resulteert in een gewijzigde lichaamsconfiguratie bij aanvang van (hielcontact) van de transitiepas. Bij de RWT zien we dat de transitie slechts is vervolledigd na eerste wandelschrede waarbij de romp wordt geherpositioneerd. Bovendien wordt het transitieproces gekenmerkt door een functionele asymmetrie, die bruikbaar is in het identificeren van de transitiezone.

Een derde onderzoek legde de nadruk op de energie-fluctuaties van het lichaamszwaartepunt (COM). Als we wandelen, fluctueren potentiële en kinetische energie van het COM uit-fase. Een deel van de energie wordt gerecupereerd door gebruik te maken van het principe van de omgekeerde slinger. Bij het lopen, echter, zijn deze energetische componenten in-fase zodat opslag en return van energie in de elastische structuren van het lichaam de enige manier is om een deel van de energie terug te winnen. Om een idee te krijgen van een dergelijke overgang van uit-fase naar in-fase energie-fluctuaties van het COM bij de mens, werd de dynamica van het COM bestudeerd tijdens een versnelling. De dynamische overgang wordt redelijk abrupt in één enkele transitiestap verwezenlijkt. Tijdens deze transitiepas is een actief geleverde energie noodzakelijk om de eerste vluchtfase mogelijk te maken en om de romp te herpositioneren in de meer voorwaarts geïnclineerde positie bij lopen. Na deze pas begint men te lopen met de typische in-fase energie-fluctuaties met als resultaat dat de energie, die wordt geleverd door de omgekeerde slinger plots daalt.

Een vierde onderzoek bestudeerde de grondreactiekracht (GRF). Daar deze de enige externe kracht is die tijdens wandelen en lopen die de dynamica van het bewegingssysteem tijdens de steunfase reflecteert, kan de GRF als dusdanig extra inzicht geven in het begrijpen van de gangtransities. De verticale GRF (vGRF) bevestigt wat in vorig onderzoek werd aangetoond, namelijk dat de eigenlijke transitie voornamelijk wordt gerealiseerd tijdens de transitiepas die wordt gekenmerkt door een afwijkend patroon van de vGRF en verloop van het drukcentrum (dit is het momentane aangrijpingspunt van de GRF-vector). Bovendien worden aanpassingen gevonden tijdens de laatste wandelpas voor de WRT-stap. Een kleinere tweede piek in de vGRF een snellere verplaatsing van het drukcentrum op het einde van de standfase werden vast gesteld. De RWT wordt zowel ‘voor’- als ook ‘nabereid’ en is slechts vervolledigd na de eerste wandelpas. De voorbereiding bestaat uit een kleinere actieve vGRF-piek tijdens de laatste looppas. Na transitie wordt een grotere eerste vGRF-piek geobserveerd tijdens de eerste wandelpas.

Het doel van de laatste studie is om de hypothese van het bestaan van een pool van determinanten na te gaan. Door de musculus tibialis anterior (TA: een relatief kleine spier die instaat voor het optrekken van de tenen) te vermoeien, werd een mogelijke trigger van transitie verzwakt. Daardoor zou de TA de zwakste schakel kunnen worden en zouden veranderingen kunnen optreden in de transitiesnelheid. WRT-snelheid is inderdaad lager na het induceren van lokale vermoeidheid in de TA. De RWT-snelheid wordt echter niet beïnvloed. Dit bevestigt dat de TA waarschijnlijk een van de determinanten uit de WRT-pool is en dat WRT en RWT worden bepaald door andere determinanten.

CONCLUSIES

Wanneer de snelheid gradueel verandert, worden gangtransities hoofdzakelijk gerealiseerd in één stap. Deze transitiepas wordt gekenmerkt door een specifieke transitie gerelateerde stap-tijd en een afwijkende kinematische en kinetische configuratie. Naast deze opmerkelijke plotse transitie worden tevens aanpassingen, gekoppeld aan de transitie, gevonden tijdens de stappen in nabijheid van deze transitiepas. Voor alle onderzochte variabelen zien we een voorbereiding van de WRT (tijdens de laatste wandelpassen). De RWT daarentegen wordt vermoedelijk ‘nabereid’ en de transitie is nog niet vervolledigd na de transitiepas maar slechts na de eerste wandelschrede zodat locomotie kan worden voortgezet in een stabiel wandelpatroon. Hoogst waarschijnlijk worden WRT- en RWT-snelheid niet uitgelokt door één enkele factor maar ligt een pool van determinanten aan de basis. Bovendien is WRT niet een spiegeling van RWT aangezien fundamentele verschillen worden gevonden in de realisatie en in de determinanten van beide transities.

Een laatste bevinding is dat de spatio-temporele, dynamische en kinematische definitie van wandelen en lopen (zie onder), die in onderzoek naar locomotie door elkaar gebruikt worden, zelfs in nabijheid van transitie overeenkomen. De uit-fase fluctuaties van energie (dynamische definitie) kenmerkend voor wandelen gaan gepaard met de aanwezigheid van een dubbele steunfase (spatio-temporele definitie) en een min of meer gestrekt steunbeen (kinematische definitie). Lopen wordt gekenmerkt door in-fase fluctuaties van energie, een vluchtfase en buiging van het steunbeen.

Publications

ACCEPTED

Segers, V., Aerts, P., Lenoir, M. and De Clercq, D. (2006) Spatiotemporal characteristics of the walk-to-run and run-to-walk transition when gradually changing speed. *Gait and Posture* **24**, 247-254.
(available online: doi:10.1016/j.gaitpost.2005.09.006)

Segers, V., Lenoir, M., Aerts, P. and De Clercq, D. (accepted for publication) Influence of m. tibialis anterior fatigue on the walk-to-run and run-to-walk transition in non-steady state locomotion. *Gait and Posture*, Accepted for publication

Segers, V., Lenoir, M., Aerts, P. and De Clercq, D. (accepted for publication) Kinematics of the transition between walking and running when gradually changing speed. *Gait and Posture,* Accepted for publication

SUBMITTED

Segers, V., Aerts, P., Lenoir, M. and De Clercq, D. (submitted) Dynamics of the body Centre-of-Mass during actual acceleration across transition speed. Submitted to *The Journal of Experimental Biology.*

Segers, V., Aerts, P., Lenoir, M. and De Clercq, D. (submitted) External forces during actual acceleration across transition speed. Submitted to *Research Quarterly for Sports and Exercise.*

Appendices

APPENDIX A

In the case of an acceleration of 0.1m s^{-2} and a step duration of 0.4s, there has to be a velocity increase of 0.04 m s^{-1} during each step. Based upon the momentum-impuls equation, this implies, on the average, a force of about 6.3 N needed for the acceleration in our experiment (average body mass = 63 kg).

$$63 \text{ kg} * 0.04 \text{ ms}^{-1} = \text{Fav}^{*} * 0.4 \text{ s}$$

$$\Rightarrow \text{Fav} = 6.3 \text{ N}$$

This represents only a small fraction of the fore-aft forces during running, which is missed when using the accelerated treadmill. Most likely, this hardly affects the magnitude and orientation of the ground reaction force vector. This is further supported by the next simulation in which the magnitude and orientation of the ground reaction force vector is compared between a 'steady' running step on the accelerated treadmill and an actual accelerated running step (0.1 m s^{-2}). The vertical and horizontal force profiles are simulated on the basis of momentum-impulse considerations (i.e. Fz averaged over an half-stride cycle equals bodyweight; impulse of Fy during ground contact equals the velocity increase during one step; cf. above and see for instance Aerts et al., 2003) are given in figure 1. The according force vectors are plotted in figure 2.

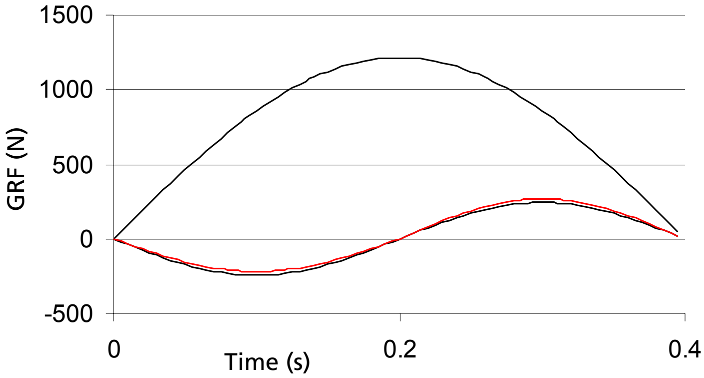


Figure 1. Differences in GRF overground (red) and on the treadmill (black).
Vertical GRF-pattern is identical.
Only fore-aft GRF are influenced. Parameters used in the simulation can be found in table 1.

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[*] Fav = average force

Table 1.

Parameters used in the simulation

		Simulation	
		Overground	Treadmill
	Body mass	63 kg	63 kg
{	Step frequency	2.04 Hz	2.04 Hz
	Duty factor	0.46	0.46
↳	Stance duration	0.4 s	0.4 s
	Δ v	0.04 m s^{-1}	0 m s^{-1}
	Fz/Fy	5	5

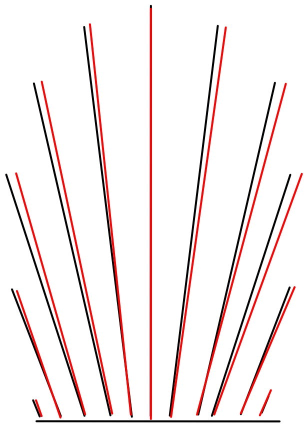

Figure 2.

Butterfly representation of the GRF at every ten percent of stance (scaled)

As can be seen in the figure above, the forces experienced by the body, more precisely by the stand limb, on the accelerated treadmill (red arrows) only differ to a small extent from the forces during overground acceleration (black arrows). Combined with the large resemblance in kinematics between overground and treadmill acceleration within the same subject (see Fig. 3, Chapter 7, p. 171), it can be assumed that for the applied treadmill acceleration the effects are negligible and will likely not affect the conclusions drawn from the study

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ISBN13 978-90-209-9655-5
ISBN10 90-209-9655-3