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The influence of ambulatory speed on gait biomechanical parameters.

KEY WORDS:

Biomechanics. Gait. Velocity.
Review of literature.

ABSTRACT

The aim of this study was to systematically review the literature of the XXI century on the effect of increased speed on gait biomechanics. Three data base (PubMed, Science Direct and Scopus) were searched from 2001 to 2010 using the terms: (gait *OR* walking *OR* walk) *AND* (velocity *OR* speed) *AND* (ground reaction forces *OR* kinetics *OR* kinematics OR biomechanical *OR* biomechanics *OR* plantar pressure *OR* electromyography *OR* mathematical model) *AND* (comparison *OR* compare *OR* change *OR* relation *OR* influence). A total of 71 papers were selected, dealing with analysis based on plantar pressure, electromyography, kinetical, and kinematical variables. Results showed that there is a consensus about the effect of increasing gait speed on the (i) duration of stance phase; (ii) stride and step frequency; (iii) stride and step length; (iv) duration of double-limb support phase; (v) duration of gait cycle; (vi) peak pressure; (vii) maximum force; (viii) vertical ground reaction force (GRF) peaks and intermediate minimum; (ix) instant of vertical GRF peaks and intermediate minimum; (x) vertical impulse; (xi) anterior-posterior GRF peaks; (xii) anterior-posterior GRF impulse; (xiii) peak of joint moments; (xiv) peak powers; (xv) mechanical work; (xvi) centre of mass amplitudes; (xvii) muscle activity.

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Influência da velocidade nos parâmetros biomecânicos da marcha.

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RESUMO

O objetivo deste estudo foi revisar de maneira sistemática a literatura publicada no século XXI sobre o efeito do aumento da velocidade na biomecânica da marcha. Artigos científicos publicados entre 2001 e 2010 e incluídos em três bases de dados (*PubMed*, *Science Direct* e *Scopus*) foram pesquisadas pelos termos: (*gait OR walking OR walk*) *AND* (*velocity OR speed*) *AND* (*ground reaction forces OR kinetics OR kinematics OR biomechanical OR biomechanics OR plantar pressure OR electromyography OR mathematical model*) *AND* (*comparison OR compare OR change OR relation* ou *influence*). Setenta e um artigos abordando aspectos referentes as pressões plantares, eletromiografia, cinemática e cinética da marcha foram selecionados. Os resultados indicam um consenso acerca do efeito do aumento da velocidade da marcha na (i) duração da fase de apoio; (ii) frequência de passo e passada; (iii) comprimento de passo e passada; (iv) duração da fase de duplo apoio; (v) duração do ciclo da marcha; (vi) pico da pressão; (vii) força máxima; (viii) força de reação do solo (FRS) vertical; (ix) instante dos picos das FRS e mínimo entre os picos; (x) impulso da FRS vertical; (xi) pico ântero-posterior das FRS; (xii) impulso ântero-posterior das FRS; (xiii) pico dos momentos articulares; (xiv) pico da potência; (xv) trabalho mecânico; (xvi) amplitudes de deslocamento do centro de massa; e (xvii) atividade muscular.

PALAVRAS CHAVE:

Biomecânica. Marcha. Velocidade. Revisão da literatura.

INTRODUCTION

Gait studies seem to be growing in number through the last years of biomechanical research. This may be explained by the increased interest in the definition of typical gait and its variability, allowing to: (i) characterize ontogenetic evolution and involution of gait; (ii) define pathological or atypical conditions; (iii) characterize the acute impact of different interventions (chirurgic, physiotherapeutic, and physical training), or (iv) characterize the impact of different performance conditions (fatigue, load, group performance, orthoses and other interfaces—like shoes, insoles, floors, etc.).

To fulfill most of the previously referred aims, it is needed to essay standardizing the performance context, namely in what concerns: (i) gait speed and (ii) ground inclination—leveled, uphill, and downhill. Among these factors, gait speed seems to be the more decisive factor to be controlled, once it should be considered in any inclination context. Moreover, we are constantly experiencing speed changes during locomotion, both because the production and application of forces (braking and propulsive) are not constant, and because the mechanisms of neuro-mechanical control are changing in time.

It is well known that walking speed influences the fundamental elements of gait—joint rotations (kinematics), ground reaction forces (GRF), net internal joint moments and joint power (kinetics), muscle activity (electromyography—EMG), and spatio-temporal parameters such as stride length, and cadence [(36)]. Furthermore, it is generally accepted that gait parameters follow a consistent pattern of change in response to varying gait speed [(32)]. However, some mechanisms, such as the one of transmitting increased impulse to the ground as walking speed increases, seems to be not yet fully understood [(39)].

With this study we aimed to expose in a systematic way, considering what has been written about this subject, the state of the art of how speed affects biomechanical gait parameters. We secondarily aimed to identify the variables that had been already studied and the consistency of the associated findings, depicting any conceptual conflict in the results obtained in the topic.

METHODS

A systematic research of studies that took in account different gait speeds was conducted in digital databases, based on inclusion and exclusion criteria previously defined. Due to its relevance and coverage, the following databases, time course of the search and domains were selected:

— PubMed (in the last 10 years, i.e. 2001 to 2010, on the title or abstract)
— Science Direct (since 2001, i.e. 2001 to 2010, on the title, abstract or key-words)
— Scopus (since 2001, i.e. 2001 to 2010, on the abstract).

RESEARCH TERMS

On the three databases selected, the following terms were searched: (gait *OR* walking *OR* walk) *AND* (velocity *OR* speed) *AND* (ground reaction forces *OR* kinetics *OR* kinematics *OR* biomechanical *OR* biomechanics *OR* plantar pressure *OR* electromyography *OR* mathematical model) *AND* (comparison *OR* compare *OR* change *OR* relation *OR* influence).

INCLUSION CRITERIA

All studies that reported effect of speed on human gait using biomechanical parameter written in English were included in this study. We only considered the studies in which the target was the typical gait analysis (without any gait dysfunction or pathology).

DATA ANALYZE

For all the selected studies, a brief characterization was done — title, authors, methods, and variables — and a synthesis of results and conclusions

RESULTS

The database search that was conducted for the first decade of the XXI century allowed to select sixty nine studies (n = 69), from which eight were excluded, because they did not satisfy the inclusion criteria. The remaining studies (N = 61) were ordered by the category of biomechanical parameters studied — plantar pressure, kinetics, kinematics, and EMG.

The results were presented in tables: the tables 1 to 4 show the results of the systematic review considering variables and by reference to results and conclusions (plantar pressure, kinetics, kinematics, EMG).

Table 1 presents the output of plantar pressure analysis, a total of 11 dependent measures were calculated: (i) time duration of the gait cycle; (ii) time duration of the stance phase (also called as contact time); (iii) time duration of the swing phase; (iv) contact area (total and per region); (v) maximum force; (vi) mean maximum force; (vii) peak pressure; (viii) mean peak pressure; (ix) mean pressure; (x) pressure-time integral and; (xi) force-time integral.

TABLE 1 — Studies using plantar pressure analysis to depict the effect of gait speed on biomechanical parameters.

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Ho et al.	Force and pressure peak	With the increase of speed, apart from the medial forefoot and hallux, the peak pressure of all regions was raised significantly; Apart from the regions of the hallux and toes, the maximum force increase significantly with increase in speed
Villaroya et al.	Time duration of the cycle, of sp and of swing phase; Peak and mean pressure	Cycle time was shorter during race walking; A large increase in the percentage of the swing and a decrease in the percentage of the sp in race walking; Peak pressure values were higher during race walking in the rearfoot and in the fourth and fifth metatarsal heads
Todd et al.	Peak pressure	Peak pressure increase with speed, except in midfoot and forefoot where peak pressure decrease as walking speed increases
Segal	Peak pressure	In the central and medial forefoot, peak pressure increased as velocity initially increased, but decreases at the fastest speed; Peak pressure and speed were linearly related in the great toe and hell
Burnfield et al.	Peak and mean peak pressure; Mean maximum force; Pressure—time integral; Contact area	Faster walking resulted in significantly higher peak and mean peak pressure values at the heel, central and medial forefoot, and toes; Mean peak pressure decreased under the lateral midfoot with faster walking speeds; Pressure—time integrals were significantly lower under all regions of the foot except for the toes with faster walking speeds; Maximum force values increased significantly with faster walking velocities; Faster walking was associated with a increase in contact area under the lateral toes, but a reduction under the lateral midfoot
Taylor et al.	Contact time; Maximum force; Peak pressure; Force—time and pressure—time integrals	With increased walking speeds, contact time decreased at all regions under the foot, as well as force-time and pressure-time integrals; Maximum force and peak pressure increased at all regions at faster walking speeds, with the exception of the lateral midfoot, medial forefoot and lateral forefoot;
Warren et al.	Peak pressure; Pressure—time integral	Speed had minimal effects on plantar pressure—time curves, except for the heel and midfoot; Peak pressures in the heel, medial forefoot and toes increase with speed

sp-stance phase

There is a general agreement among the papers showed in Table 1. Changing walking speed leads to changes in plantar pressure parameters—but not in all foot regions, with an increase of plantar pressure and plantar force as the speed increased, while there was a decrease in stance time duration and gait cycle duration in slow gait speed. However, it is important to note that the foot division (in regions) was different among the mentioned studies. The number of foot regions analyzed varied between two [(13)] and ten [(39)] in the studies.

Table 2 presents the output of the systematic literature relative to kinetic analysis, considering selected variables, results and conclusions.

TABLE 2 — Studies using kinetic analysis to depict the effect of gait speed on biomechanical parameters.

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Chung & Wang	Vt GRF first and second peaks and intermediate minimum	Vt GRF first peak increased while Vt GRF intermediate minimum decreased with the increase of walking speed
Rita	Time duration of sp	The difference between the start and end of phase thus decreased with increased gait speed
Caravaggi et al.	Time duration of sp; Vt GRF first and second peaks and intermediate minimum; Time to Vt GRF first and second peaks and intermediate minimum; Ap GRF breaking and propulsive peaks; Time to Ap GRF breaking and propulsive peaks	Time of heel-rise and of positive onset of Ap GRF decreased with walking speed, as well as Vt GRF intermediate minimum; Vt GRF first peak and Ap GRF peaks increase with the increase of speed
Lewek	Time duration of sp; Ap impulse; Peak ankle moment and power	As gait speed increased, a significant increase in propulsive impulse was exhibited, as well as ankle joint moment and power generation; There is a decrease of sp with the increase of speed
Grabowski	Stride frequency; Contact time; Vt GRF first and second peaks	Vt GRF first peak was greater when walking faster, but second peak did not significantly change with speed; Stride frequency increase as speed increase, while contact time decrease
Vito et al.	Peak hip, knee and ankle moment and power	Peak hip extension and peak ankle plantar flexor moments significantly increased with speed, as well as peak hip concentric, peak knee and peak ankle generated powers; Peak knee flexion moment decreased with speed
Robbins & Maly	Peak knee moment; Knee moment impulse	Peak knee adduction moment for the slow condition was greater than fast condition, as well as knee adduction moment impulse
Xu et al.	Time duration of the cycle, of single support and of double support; Vt GRF first and second peaks and intermediate minimum	Increasing walking speed, Vt GRF intermediate minimum decreased, but Vt GRF first and second peaks increased, while single support time, double support time and cycle time decrease
Browning et al.	Step width; Mechanical work	Step width did not change significantly with walking speed; Total positive external mechanical work and negative mechanical work increased as speed increased
Stoquart et al.	Time duration of sp; Peak hip, knee and ankle moment and power	Sp duration decreased with increasing speed; Peak hip, peak knee and peak ankle plantar flexor joints moments increased with speed, as well as peak hip, peak knee and peak ankle generated joints powers
Saha et al.	Time duration of single support and of double support; Vt GRF first and second peaks and intermediate minimum	Single support time increased with speed while double support time decreased; Vt GRF first and second peaks increased with walking speed, while Vt GRF intermediate minimum decreased

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Michael et al.	Time duration of sp and of double support; Vt GRF first and second peaks and intermediate minimum; Ap GRF breaking and propulsive peaks; Peak hip, knee and ankle moment and power	Sp and double support both decrease with increasing speed; Vt and Ap GRF peaks increased with increase of speed, while Vt GRF intermediate minimum decreased; Peak hip, peak knee extension/ flexion and peak ankle plantar flexor moments increased with speed, as well as peak hip, knee and ankle powers
Teixeira-Salmela et al.	Peak hip, knee and ankle power; Mechanical work	Peak hip, knee and ankle power trend to higher values as cadence increased; Positive mechanical work and negative mechanical work increased as speed increased
Orendurff et al.	Ap GRF breaking and propulsive peaks; Peak ankle moment and power	Breaking and propulsive peak of Ap GRF increased with speed; Peak ankle moment and power was greater at faster speed
Colné et al.	Time duration of double support	Double support time decreases when gait speed increases
Seeley et al.	Vt and Ap impulse	As speed increase, Vt impulse decreased, while Ap impulse increased
Hreljac et al.	Peak knee and ankle moment and power	Peak ankle plantar flexor moment and knee extensor moments increased significantly with speed, as well as peak ankle power absorption, knee power absorption and knee power generation
Chiu & Wang	Vt GRF first and second peaks and intermediate minimum	Faster walking speed generated a higher first Vt GRF peak and lower Vt GRF intermediate minimum
Jordan et al.	Stride and step length and time duration; Vt GRF first peak; Time to Vt GRF first peak; Vt impulse; Contact time	Significant decrease in stride and step time duration, contact time duration, Vt impulse and time to Vt GRF peaks with the increase of speed; Vt GRF first peak increases with speed, as well as step and stride length
Kimberlee et al.	Stride and step length and time duration; Vt GRF first and second peaks and intermediate minimum; Vt impulse	Vt impulse, Vt GRF intermediate minimum and stride and step time duration decreased with increasing speed; Vt GRF first and second peaks increased as speed increased, as well as stride and step length
Rao et al.	Peak hip, knee and ankle moment	Peak hip, peak knee and peak ankle moments increased with increasing walking speed;
Bishop et al.	Ap GRF breaking peak	Ap GRF braking peak of the lead limb increased as cadence increased
Biewener et al.	Peak hip, knee and ankle moment	With an increase in speed, peak joint moments increased at the hip and at the knee, while peak ankle joint moment remained constant
Tammy & Mark	Step length, width and time duration	Step length increased with speed, while step width and time duration decreased as speed increased
LaFiandra et al.	Stride length and frequency	Stride length as well as stride frequency increased with speed

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Goble et al.	Time duration of sp; Vt GRF first and second peaks and intermediate minimum; Time to Vt GRF first and second peaks and intermediate minimum; Ap GRF breaking and propulsion peaks; Time to Ap GRF breaking and propulsion peaks	High velocity significantly increased Vt and Ap GRF's first and second peaks, as well as time to second peak of Vt and Ap GRF's and time to Vt GRF intermediate minimum; Time to Vt GRF first peak, Vt GRF intermediate minimum and sp decreased significantly as velocity increased
Lelas et al.	Peak hip, knee and ankle moment and power	Peak hip, knee and ankle moments and powers increased as speed increase
Hsiang & Chang	Vt GRF first and second peaks and intermediate minimum	Walking speed increase first and second Vt GRF peaks, but decreases Vt GRF intermediate minimum
LaFiandra et al.	Peak lower body moment	Increases in walking speed were accompanied by increases in lower body moment
Masani e tal.	Vt GRF first and second peaks ; Ml GRF first peak; Ap GRF breaking and propulsive peaks	For Vt and Ml GRF, there was an increasing trend in variability with speed; There was a speed at which variability was minimum for Ap GRF
Funato et al.	Mean horizontal GRF	In sprinting, constant increases in velocity were accompanied by increases in horizontal GRF
Riley et al.	Peak hip, knee and ankle moment and power	Peak hip, knee and ankle joint moment and power increased with speed

Vt-vertical; Ap-anterior-posterior; Ml-medial-lateral; sp-stance phase

Selected variables were a total of twenty six [26]: (i) vertical GRF first peak; (ii) time to vertical GRF first peak; (iii) vertical GRF second peak; (iv) time to vertical GRF second peak; (v) vertical GRF intermediate minimum; (vi) time to vertical GRF intermediate minimum; (vii) anterior-posterior GRF breaking peak; (viii) time to anterior-posterior GRF breaking peak; (ix) anterior-posterior GRF propulsive peak; (x) time to anterior posterior GRF propulsive peak; (xi) medial-lateral GRF first peak; (xii) mean horizontal GRF; (xiii) vertical impulse; (xiv) anterior-posterior impulse; (xv) peak joint moment; (xvi) peak joint power; (xvii) mechanical work; (xviii) moment impulse; (xix) stride frequency; (xx) stride or step time duration; (xxi) stride or step length; (xxii) step width; (xxiii) time duration of gait cycle; (xxiv) time duration of single support; (xxv) time duration of double support and; (xxvi) time duration of stance phase or contact time.

In the kinetic analysis the most common variables were the GRF peaks—vertical and anterior-posterior components. Moreover, also using GRF curves others variables, such as joint moments, powers, and impulses were calculated. Table 2 shows that an increase or a decrease of walking speed induces changes in both kinetic and general gait parameters, especially GRF curves and peak moments and powers, that increase as speed increases, and time duration of the stance phase, that decreases.

Table 3 presents the output of kinematic analysis: selected variables, main results, and conclusions.

TABLE 3 — Studies using kinematics to depict the effect of gait speed on biomechanical parameters.

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Chung & Wang	Hip, knee and ankle joint motion	Walking speed effect was significant in hip flexion/ extension and knee flexion increase of motion; Walking speed effects on ankle joint motion were not so obvious
Riley et al.	Hip joint motion; Pelvis motion	Hip flexion/ extension and pelvic tilt ranges of motion increased significantly for running compared to walking
Caravaggi et al.	Foot joint motion	Late-stance peak dorsiflexion increased at all metatarsophalangeal joints with faster gaits, while medial longitudinal arch showed a decreased range of motion
Dubbeldam et al.	Step length; Stride length, time duration and width; Time duration of double support; Foot and ankle joint motion	Stride length increased with speed, as well as ankle, medial arch, hallux and rearfoot motion, while stride and double support time duration decreased and stride width remain constant
Lewek	Step length	Increasing gait speed, step length increase significantly
Caekenberghe et al.	Step frequency and length; Time duration of flight phase	Higher speed was paralleled by a larger step length and a higher step frequency of the transition step in the highest acceleration Flight phase duration was significantly lower for the lowest acceleration
Franz et al.	Stride length; Hip joint motion; Pelvis and thigh motion	Stride length increased with speed; Thigh extension and pelvic motion were greater during running, as well as hip extension
Foissac et al.	Trunk motion	There is an increase in vertical displacements of the trunk when speed increases
Manor et al.	Stride time duration; Hip, knee and ankle joint motion	A significant effect of speed at stride duration variability; There was no effect of speed on joint angle variability of the hip, knee, or ankle joints
Vito et al.	Stride length; Time duration of sp; Peak hip, knee and ankle joint motion	Stride length increased with speed; There were no significant differences in sp and in peak hip, knee and ankle motion
Tulchin et al.	Time duration of double support, of single support and of sp;Ankle and foot joint motion	There was an increase in single support time with increasing walking speed and a decreases in double support time, and sp; With increasing speed, ankle, rearfoot and forefoot maximal dorsiflexion decreased and maximal plantar flexion increased
Shung et al.	Peak spine and tibia acceleration	The peak acceleration always increased at tibia and spine as the walking speed increased

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Kong & De Heer	Stride frequency, length and length relative to height; Time duration of sp	As speed increased, sp decreased while stride frequency, stride length and relative stride length increased
Stoquart et al.	Step frequency; Hip, knee and ankle joint motion	Step frequency increased with speed; Hip extension, knee flexion and ankle plantar flexor peaks increased with walking speed
Saha et al.	Step length; Hip, knee and ankle joint motion	Step length increased as speed increased as well as hip flexion and ankle plantar flexion increased; Knee flexion remained constant with increasing speed and ankle dorsiflexion decreased
Michael et al.	Hip, knee, ankle and foot joint motion; Trunk and pelvis motion	Trunk obliquity and rotation, pelvic and hip movement and knee flexion and ankle plantar flexion peaks increase as speed increase; Anterior tilt and ankle dorsiflexion decrease as speed increase; Foot progression remain constant
Sharpe et al.	Trunk and pelvis motion; Relative phase between trunk and pelvis	Trunk motion decreases as speed increases, while pelvic rotation decrease and then increase; Pelvis—trunk relative phase increased to a greater extent as speed increased
Orendurff et al.	Step length	Step length increased with walking speed
Chiu & Wang	Hip, knee and ankle joint motion; Lumbar motion	Hip, knee and ankle did not have significant differences; Increased walking speed caused an increase in lumbar motion
Paschalis et al.	Hip, knee and ankle joint motion, Pelvis motion	There is an increases of pelvic tilt and no changes in pelvic obliquity and rotation as speed increase; Hip flexion increase while hip extension decrease, from walking to running; Knee motion increase with speed, as well as ankle motion
Olivier & Cretual	Radius of curvature	Speed/ curvature relation is not ensured all the time over the locomotor path
Hanlon & Anderson	Knee and ankle joint motion	First peak knee motion increased as speed increased, while peaks ankle motion decreased
Van Emmerik et al.	Stride time duration; Time duration of swing phase and of sp; Head, trunk and pelvis motion	Stride, sp and swing duration decreased as speed increase; Trunk lateral flexion and pelvis obliquity increased with speed, as well as lumbo-sacral joint motion and pelvis-trunk axial rotation and lateral flexion; Head flexion-extension and pelvis axial rotation decrease initially and then increase as speed increases; Head lateral flexion and axial rotation, trunk flexion-extension and axial rotation and pelvis-trunk flexion-extension decrease as speed increase;
Saunders et al.	Lumbar and pelvis motion	With transition from walking to running lumbo-pelvic motion decreased; There was a trend for decreased axial rotation with a change from walking to running
Lee et al.	Stride length; Hip joint motion; Pelvis motion	Stride length increased with walking speed, as well as peak hip extension; changes in anterior pelvic tilt were not so evident
Dierick et al.	Amplitude of centre of mass	Vertical and the forward amplitude of centre of mass increased with walking speed while lateral amplitude of centre of mass decreased
LaFiandra et al.	Hip joint motion; Trunk and pelvis motion	Increasing walking speed was associated with increases in trunk rotation, pelvic rotation and hip excursion
Holt et al.	Knee joint motion; Amplitude of centre of mass	There was increases in knee excursion as a function of walking speed; Vertical amplitude of the centre of mass increased with speed

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Lelas et al.	Hip, knee and ankle joint motion	Peak hip flexion and extension and peak knee flexion and extension trend to increased with speed; Peak ankle planter flexion in loading response and ankle dorsiflexion during mid stance trend to decrease as speed increase, as peak plantar flexion and dorsiflexion during swing trend to increase
Ivanenko et al.	Time duration of sp; Stride length	Stride length increased with speed while sp decreased
LaFiandra et al.	Thoracic and pelvis angular acceleration	Increasing walking speed resulted in increases for pelvic and thoracic angular acceleration

sp-stance phase

In kinematic studies, it was possible to find, beside joint motion analysis, the study of general gait parameters, like stance time, step length and width, double and single support time. Selected variables were a total of 16: (i) segment and joint motion; (ii) peak acceleration; (iii) angular acceleration; (iv) relative phase (difference in time between the peaks of the two segment angles within each stride cycle); (v) radius of curvature; (vi) walking effort; (vii) amplitude of centre of mass; (viii) stride and step frequency; (ix) stride time duration; (x) stride and step length; (xi) stride width; (xii) time duration of single support; (xiii) time duration of double support; (xiv) time duration of flight phase; (xv) time duration of swing phase and; (xvi) time duration of stance phase.

Papers from Table 3 are in agreement, with the exception of Kong and De Heer [29], who did not find differences in time duration of stance when changing speed, while Tulchin et al. [56], Van Emmerik et al. [57] and Vito et al. [59] found a decrease in stance time while increasing speed.

Table 4 presents the output of EMG analysis, considering selected variables, results and conclusions.

TABLE 4 — Studies using electromyography analysis to depict the effect of gait speed on biomechanical parameters.

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Chung & Wang	EMG activity of bicieps femoris, rectus femoris, tibialis anterior, and medial gastrocnemius	The EMG response in tibialis anterior, in rectus femoris and in medial gastrocnemius increased with increasing walking speed; The effect of walking speed on bicieps femoris was not significant as the other muscle groups
Lewek	Muscle activity of soleus and medial and lateral gastrocnemius	The magnitude of soleus, and medial and lateral gastrocnemius activity significantly increased with each incremental increase in gait speed

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Schmitz et al.	EMG activity of soleus, gastrocnemius, biceps femoris, medial hamstrings, tibialis anterior, vastus lateralis, and rectus femoris	At loading phase, tibialis anterior, soleus, biceps femoris, and rectus femoris activities increased as speed increased; At mid-stance, gastrocnemius and biceps femoris activities increased as speed increased; At terminal stance and pre-swing, tibialis anterior, gastrocnemius, biceps femoris, vastus lateralis, medial hamstring, and rectus femoris activities significantly increased as speed increased; At initial swing, only rectus femoris activity significantly increased as speed increased; At terminal swing, biceps femoris and medial hamstring activity increased with speed
Kang & Dingwell	EMG linear envelopes of vastus lateralis, biceps femoris, medial gastrocnemius, and tibialis anterior	Variability of individual EMG linear envelopes increased with speed in vastus lateralis, biceps femoris and tibialis anterior, except in gastrocnemius; Peak EMG amplitudes increased with speed for vastus lateralis, biceps femoris, medial gastrocnemius, and tibialis anterior
Shung et al.	Average EMG values of tibialis anterior, vastus lateralis, and erector spinae	The EMG of tibialis anterior, vastus lateralis, and erector spinae muscles increased as the speed increased during walking, but this was not observed during running
Stoquart et al.	Muscle activity time and duration of quadriceps femoris, biceps femoris, tibialis anterior and lateral gastrocnemius	Time and duration of activation phases changed with speed; The duration of the first burst in quadriceps femoris, biceps femoris and tibialis anterior decreased with speed; The end of the first burst in lateral gastrocnemius occurred sooner with speed; At the end of stance, tibialis anterior was the only muscle active
Michael et al.	Muscle activity of rectus femoris, medial and lateral hamstrings, anterior tibialis and medial gastrocnemius	Changes in EMG were characterized by amplification of peak values with increasing speed in rectus femoris, medial and lateral hamstrings, anterior tibialis and medial gastrocnemius
Chiu & Wang	EMG activity of bilateral lumbar erectors spinae, biceps femoris, rectus femoris, medial gastrocnemius and tibialis anterior	Walking faster generated significantly higher EMG response in the lumbar erector spinae, biceps femoris, and medial gastrocnemius muscles, in the rectus femoris and tibialis anterior there is also an increased at fast speed, but not significantly
Chumanov et al.	EMG activities of biceps femoris, medial hamstrings, vastus lateralis, rectus femoris, and medial gastrocnemius	The influence of biceps femoris, medial hamstrings, vastus lateralis, rectus femoris, and medial gastrocnemius on hamstring stretch was larger at maximal speed
Ishikawa et al.	Pre-activation of medial gastrocnemius; Braking phase EMG activity medial gastrocnemius; Push-off phase EMG activity medial gastrocnemius	Compared to walking, the medial gastrocnemius average EMGs were greater in the pre-activation and braking phases of running; In the push-off phase average EMG of the medial gastrocnemius was greater at walking
Saunders et al.	EMG activity of multifidus deep and superficial fascicles, obliquus externus and internus abdominis, transversus abdominis, rectus abdominis and, erector spinae	With increased running speed there was no change in timing of peak EMG for any muscle, but the EMG activity of multifidus deep and superficial fascicles, obliquus externus and internus abdominis, transversus abdominis, rectus abdominis and, erector spinae increased with speed

AUTHORS	VARIABLES	RESULTS/ CONCLUSIONS
Bishop et al.	Muscle activity of gluteus medius, hamstring and, soleus muscles; Relative EMG timing of gluteus medius, hamstring and, soleus muscles	There was no main effect noted for cadence in the relative EMG timing of gluteus medius, hamstring and soleus muscles; As cadence increased, the onset of muscular activity occurred closer to heel-strike for gluteus medius, while soleus onset was more rapid after heel-strike
Warren et al.	EMG activity of tibialis anterior and medial gastrocnemius	Speed had minimal effects on the shapes of the muscle EMG RMS; There is a significant increases in peak EMG RMS from the slowest to the fastest speed for tibialis anterior and medial gastrocnemius muscle
Ivanenko et al.	EMG activity of gluteus maximus, vastus lateralis, rectus femoris, biceps femoris, tibialis anterior, and lateral gastrocnemius	Mean activity of gluteus maximus, vastus lateralis, rectus femoris, biceps femoris, tibialis anterior, and lateral gastrocnemius tended to increase exponentially with speed, though the increment was not always monotonic

Most of the studies were focused on muscle activity of different muscles or muscle groups. The concept of "EMG activity" presented, however, slightly different approaches like average peak, or maximum peak. Relatively to muscle activity—peak muscle activity or mean muscle activity—all papers are in agreement. An increase of speed leads to an increased muscle activity.

DISCUSSION

This study aimed to systematize the current state of the art regarding the effects of speed on the gait biomechanics. The idea that gait parameters should change with locomotion speed is easily traduced by the empirical observation that, increasing gait speed from very low to very high, will imply a transition from walking to running; two modes of bipedal locomotion with important differences separating them.

In continuation we will discuss the contents of each one of the tables separately, first in order to variables and secondly in order to results and conclusions, following the four biomechanical parameters used. We will finish with an integrated discussion of the analyzed body of knowledge.

METHODS AND VARIABLES

Considering plantar pressure analysis, the most of the studies used in-shoe plantar pressure systems [5, 20, 49] or a pressure plates [39, 54]. In-shoe systems and pressure platforms allow dividing the footprint in different zones—some authors divided the foot in eight regions, others in ten, others in five and others in nine — this division of foot depends of the interest regions of the study. Villaroya [58], however, used a pressure insoles telemetric system with only six sensors. In this case, and due to instrumental limitations, the author refrains to study only two regions of the foot: rearfoot and forefoot.

Peak pressure, maximum force, and duration of stance phase were the most studied variables in plantar pressure protocols. All papers analyzed peak pressure pressure [5, 13, 20, 39, 49, 60]. Other calculated variables were contact area, force-time integral, pressure-time integral, mean pressure, time duration of swing and time duration of the gait cycle.

Only one author [52], used isolated strain gauges to measure GRF, while all of the others used force plates. Both methods are appropriated to measure GRF. However, force places are widely accepted as the "gold standard" for this purpose in gait analysis, reason why its use is spread worldwide (in fact, only one study used a load cell). Furthermore, it can be said that force plates are very accurate and reliable instruments, reason why the results obtained through this type of instrument are in so close agreement. Vertical and anterior-posterior GRF peaks were the most analyzed parameters.

Relatively to the kinematic methods, the most part of the authors used optoelectronic motion-capture systems. The exceptions were Foissac et al. [15] and Shung et al. [51], who used accelerometers, whereas Dubbeldam et al. [14], Hanlon and Anderson [19] and Manor et al. [34] that used videogrametry systems. Although both videogrametry and optoelectronic systems are commonly used to capture and study body motion, the optoelectronic systems are considered to be more accurate in laboratory conditions use. Accelerometry was used only in trunk motion and for peak spine and tibia acceleration analysis.

In terms of kinematic analysis the most part of studied variables did not present consensual results among studies. This can be explained by the low reliability of some of the methods available. Only variables that present great differences are showed to be in agreement, like general gait parameters such as stride and step frequency, stride and step length, time duration of gait cycle, time duration of stance and time duration of double support phase.

Electromyography is the only method to measure muscle activity. This analysis can be made by surface and implanted electrodes. The most studies used surface EMG; only Saunders et al. [46] used implanted electrodes, and mixed with surface electrodes to allow monitoring also deep and superficial muscles.

GAIT PARAMETERS

General gait parameters can be studied using plantar pressure, kinetic or kinematic protocols. Most of the gait parameters studied showed to be influenced by gait speed. For the duration of the gait cycle—stride or step— in general, as walking speed increase this variable decrease [13, 14, 26, 28, 53, 57, 61]. Thus, stride or step frequency, and stride or step length, as well as time duration of the various phases of gait cycle—stance, swing, double support, single support— are affected by an increase or decrease of gait speed. As we expected, stride [18, 30] and step [6, 29, 52] frequency increased as speed increased. Stride and step length [6, 14, 16, 25, 26, 28-31, 33, 37, 45, 53, 59] also increased with walking speed. Stride width was also analyzed in three studies [4, 14, 53]. This variable did not seem to be influenced by gait speed, however there were some statistical tendencies for finding influence [53]. Nevertheless, further research is needed, inclusively regarding the expected role of this parameter in gait dynamical balance.

Relatively to the time duration of the stance phase, almost all papers showed a decrease [7, 17, 18, 25, 29, 33, 36, 43, 52, 54, 56, 57, 58] with the increase of walking speed, except Vito et al. [59] who found no significant differences. This discrepancy may be explained by the low differences between the speed intervals studied in the late report, which was determined by the method used to choose gait speed—based on the principle of dynamic similarity. Only Caekenberghe et al. [6] observed what happens to the swing phase, during running, this increased as acceleration increased.

There was no agreement on the effect of changing walking speed on the time duration of swing phase. To Villaroya et al. [58], the increase of speed leads to an increasing of time duration of the swing phase normalized to time duration of gait cycle, and to Van Emmerik et al. [57], the opposite seems to happen. This could be due to the fact that the first author used a plantar pressure protocol to identify the swing phase time duration, while the second used a kinematical approach. Nevertheless, it should be emphasized that both options seem appropriated for the purpose, and further investigation is needed on this particular topic.

The duration of the stance phase and double support phase decreased as walking speed increased [11, 14, 36, 45, 56, 61]. This behavior seems to be completely consensual among literature. The relatively reduced dynamical stability of gait due to the reduced double support phase may contribute to a compensation effect that, in some cases, may be traduced by an increased step width.

The effect of increasing gait speed on the time duration of single support time is not consensual. Tulchin et al. [56] and Saha et al. [45] described that with an increase of speed, single support duration time also increase. On the other hand, Xu et al. [61] found that it decrease as walking speed increase.

PLANTAR PRESSURE

The most used variable in plantar pressure studies was the peak pressure. This variable was analyzed in all papers that used this kind of protocols [5, 20, 39, 49, 54, 58, 60]. Each paper divided the foot in a different number of regions, Villaroya et al. [58] was the only that divide the foot in rearfoot and forefoot regions. The others divided the foot in five [49], eight [5, 20], nine [54, 60], and ten [39] regions. The most studied foot regions were the hallux, the forefoot and the heel. In general, all papers considered that peak pressure increased significantly at heel, toes and hallux as speed increases—except for Ho et al. (20) who observed that at the hallux, the increase in peak pressure with speed is not statistically significant. Medial and central forefoot peak pressure increased significantly and consensually with increasing walking speed (5, 20, 49, 54, 60). Lateral forefoot and midfoot peak pressure results present some disagreements among published studies. Todd et al. (39) considers that there is a decrease in peak pressure at these two foot regions while increasing gait speed. However, for Ho et al. (20) and Taylor et al. (54), there is an increase in these two regions; whereas other authors (5, 49, 60) found no differences in peak pressure at the lateral forefoot related to speed variation. More studies are needed to clarify this issue.

Burnfield et al. (5) also analyzed the mean peak pressure. Their findings were similar to those obtained for peak pressure. When the gait speed was higher, the mean peak pressure increased at hallux, toes, heel, central and medial forefoot, and remain unchanged at midfoot and lateral forefoot. On the other hand, Villaroya et al. (58) showed lower values of mean pressure at the forefoot as walking speed increased. This incongruence may be due to the fact that Burnfield et al. (5) used the an in-shoe plantar pressure system with 99 capacitive sensors, while Villaroya et al. (58) used an in-shoe system with six piezo-resistive sensors.

Pressure-time integral was studied by several authors (5, 54, 60) concluded that speed affect significantly pressure-time integral at the heel and midfoot. As walking speed increased the pressure-time integral at heel, midfoot and forefoot—central, medial and lateral—decreased, and at hallux and toes there is no significant change. The reduced pressure-time integral at the heel may be related to an increased contact area with speed, and/ or to a reduced contact time, once, as we will see, the first peak value of the vertical component of the GRF seem to increase with speed. In accordance, force-time integral, as same as pressure-time integral, decrease at all foot regions—heel, midfoot and forefoot—except at hallux and toes (54).

Maximum force and mean maximum force, as well as the peak pressure, increase in almost all foot regions. All the authors (5, 20, 54) are in agreement relatively to maximum force at heel, which increases significantly with speed. To hallux and toes, authors found that there is either an increase (5, 54) or similar values (20) while increasing gait speed. According to Burnfield et al. (5) and Taylor et al. (54), maximum force at medial and lateral midfoot remain constant as speed increase, as well as at the lateral forefoot. To medial and central forefoot, Ho et al. (20) found an increase of this variable with speed, while Burnfield et al. (5) showed that central forefoot maximum force remains unchanged and that there is an increase in medial forefoot, while Taylor et al. (54) demonstrated the opposite—in the medial forefoot the maximum force remained unchanged and in the central forefoot increased as speed increased. Once more, new approaches should be conducted to clarify these effects.

KINETICS

All papers are in agreement in what concerns the effect of walking speed on vertical GRF peaks and intermediate minimum between the peaks [7, 8, 10, 17, 23, 26, 28, 36, 45, 61] and correspondent times of occurrence [7, 17, 26]. As speed increases, vertical GRF first peak increase significantly while vertical GRF second peak did not show significant differences, and vertical GRF intermediate minimum decreases significantly. Time to vertical GRF first peak decreases significantly, while time to vertical GRF intermediate minimum and time to vertical GRF second peak increase significantly.

Both, braking and propulsive anterior-posterior GRF peaks increased significantly with walking speed [3, 7, 17, 36, 37]. In accordance to Goble et al. [17], the time to both anterior-posterior GRF peaks increased with walking speed. However, Caravaggi et al. [7] found no change in these parameters as speed increased. The increase with gait speed of the anterior-posterior GRF peaks can also be observed in the mean values of the two horizontal components of the GRF—anterior-posterior and medial-lateral.

Masani et al. [35] analyzed the variability of three GRF components as speed changing. They found that variability of vertical and medial-lateral GRF increased as speed increased, while, on the other hand, anterior posterior GRF showed a critical speed at which the variability was minimal. With these results, Masani et al. [35] suggested that there is an optimum speed for propulsion control mechanism.

Based on vertical and anterior-posterior GRF, there is another relevant variable often analyzed by the different research groups: the impulse (vertical or anterior-posterior). Vertical impulse and anterior-posterior impulse seem to have opposite behavior. The first one decreases significantly [26, 28, 48] as speed increases, while the second one increases significantly [33, 48]. The impulse of a force is both determined by its intensity and by the time duration of its application. As a consequence, the high vertical impulse values characteristic of slow gait may probably be explained by the higher stance phase duration rather than force intensity. Meanwhile, horizontal impulses are related to sheer stress applied to the contact surfaces (plantar surface of the feet), possibly being related to plant foot related-injuries [2].

Peak moments were analyzed at the hip, knee and ankle. Generally, the peak moment in the hip, knee, and ankle [1, 32, 40, 41, 52] increased with speed. Vito et al. [59] and Michael et al. [36] found a significant increase in hip extension moment with speed. Peak knee flexion [22, 36, 59] and adduction [44] decreased as speed increased. Concerning peak ankle moment, although there was one study that reports no changes [1], several others [22, 36, 52, 59] found an increase of plantar flexor moment with gait speed, which seem to be coherent with the increase of anterior-posterior horizontal GRF values.

Same to peak joint moments, peak joint power values were analyzed at hip, knee and ankle. Based on most papers [32, 36, 41, 52, 55, 59] we can observe that the increasing in peak hip power was the most specific and reported as significant when speed increases. The peak knee power showed higher values as speed increased as well [32, 36, 41, 52, 55, 59]. In general, peak ankle power also increased with speed [36, 55].

Mechanical work of lower limb has been studied by Browning et al. [4] and Teixeira-Salmela et al. [55]. The findings of both papers are in agreement: mechanical work, positive or negative, increased as speed increased.

KINEMATICS

Kinematic study consists essentially in joint motion analysis—hip, knee, ankle and foot—and segment motion analysis—head, trunk, lumbar, pelvis and thigh.

At head, it was observed a significant decrease in lateral flexion and axial rotation when speed increases [57]. Michael et al. [36] and Van Emmerik et al. [57] found a decreased in trunk tilt and a decrease in flexion-extension motion, respectively. Despite that, a significant increase of vertical displacements of trunk was observed by Foissac et al. [15]. Obliquity [36] and lateral-flexion [57] of the trunk also increased as speed raised. Regarding trunk rotation, some disagreements were perceived in the studied literature that justify further research: on one hand, LaFiandra et al. [30] and Michael et al. [36] found an increase in trunk rotation and, on the other hand, Van Emmerik et al. [57] observed that axial rotation decrease with the increase of walking speed. Thigh extension motion also increased as speed increased [16].

In general, pelvis motion increase significantly with speed [16, 36], as well as lumbar motion [8]. There is no consensus in pelvic tilt, rotation and obliquity motion and further approaches are needed. For Paschalis et al. [38] and Riley et al. [42], pelvic tilt increase with speed, whereas for Lee et al. [31] and Van Emmerik et al. [57] it remained unchanged. Concerning pelvic obliquity, Paschalis et al. [38] did not note any change, while Van Emmerik et al. [57] found a significant increase with gait speed. Relatively to pelvic rotation, in one study no alterations were observed [38], while in others either an increase [30] or decrease [50, 57] were described. Again, new insight is needed.

Disagreements were also found concerning general hip movement. Some studies stated that there is no significant changes with gait speed [8, 59], while LaFiandra et al. [30] found an increased movement. Several authors [10, 32, 36, 38, 42, 45] agree that hip flexion increases as walking speed increases; however, some other disagree about hip extension motion: to Lee et al. [31] there is an increase of hip extension motion, while Paschalis et al. [38] observed a decrease, and Franz et al. [16] found no significant changes. This discrepancy among the author's observations may be due to the walking speeds chosen; Paschalis et al. [38] only studied two different speeds, which were much higher than those used by the others authors.

Saunders et al. [46] report a decrease of axial rotation of lumbar-pelvic motion with the increase of gait speed.

Is general, authors agree that knee flexion motion increase [10, 19, 21, 32, 36, 38, 52] with the increase of walking speed. Only Saha et al. [45] found that knee motion remain unchanged, while others [8, 34, 59] refer that there is no significant change.

Considering ankle motion, Dubbeldam et al. [14] and Paschalis et al. [38] found increased ankle motion with higher gait speeds, but the opposite was also found in other studies [8, 10, 19, 34], whereas Vito et al. [59] found no differences. Dorsiflexion motion decreased [36, 45, 56] while plantar flexor increased [36, 45, 52, 56] as speed increased. Meanwhile, Lelas et al. [32] noted that, during the swing phase, both plantar flexion and dorsiflexion increased, while during stance phase this two movements decreased.

Foot joint motion does not change significantly with speed [36]. There are some disagreements between studies when analyzing the different foot regions separately. For Dubbeldam et al. [14], medial arch motion increases as speed increases, but the same did not happen in the results obtained by Caravaggi et al. [7]. Rearfoot motion increased with speed [14], but with a possible slight decrease of rearfoot dorsiflexion and an increase of plantar flexion [56]. Tulchin et al. [56] found a similar behavior of forefoot motion—a decrease of dorsiflexion motion and an increase of plantar flexion motion—but Caravaggi et al. [7]. reported that forefoot dorsiflexion increased as walking speed increased. Only Dubbeldam et al. [14] analyzed hallux and found an increased of motion while increasing gait speed.

Centre of mass amplitudes of movement has also been studied [12, 21]. Both studies found an increased vertical amplitude as speed increased, but Dierick et al. [12] also found that forward amplitude increased and lateral amplitude decreased in higher gait speeds.

ELECTROMYOGRAPHY

In general, it is possible to state that the gait speed affects the amplitude, timing and duration of the muscle activity. Fot the vastus lateralis, rectus femoris, biceps femoris, medial and lateral hamstrings, tibialis anterior, medial and lateral gastrocnemius, gluteus maximus, soleus, erector spinae, multifidus, obliquus abdominis, transversus abdominis and rectus abdominis there was an increase in their EMG amplitudes as speed increased [9, 10, 25, 27, 33, 36, 46, 51, 60]. Moreover, the EMG amplitudes of biceps femoris, vastus lateralis and tibialis anterior increase their variability with walking speed [27], which means that the increase with the speed is not always the same.

Schmitz et al. [47] was the only that studied the increase of muscle activity along each gait cycle phase as speed increases; however, Stoquart et al. [52] and Ishikawa et al. [24] analyzed what happened at the end of stance phase and at braking and push-off phases, respectively (the last one only studied the medial gastrocnemius). From these analyses, it can be understood that the increase of activity with speed is also gait cycle phase dependent. During the loading phase, Schmitz et al. [47] found that there is an increase of the activation of tibialis anterior, soleus, biceps femoris and rectus femoris; to midstance, an increase of gastrocnemius and biceps femoris activation was observed. Ishikawa et al. [24] refer that medial gastrocnemius increased activity happens during the pre-activation and braking phases. At terminal stance and pre-swing phase, Stoquart et al. [52] also found higher activation of tibialis anterior and gastrocnemius. Meanwhile, for Ishikawa et al. [24] there is a decrease of gastrocnemius activaty, while vastus lateralis, medial hamstring and rectus femoris are active; at initial swing only rectus femoris increase his active and at terminal swing biceps femoris and medial hamstring.

Timing of activation of gluteus medius and soleus occur earlier when walking speed increases [3], and the duration of the activation of quadriceps femoris, biceps femoris and tibialis anterior decrease as speed increases [52].

CONCLUSIONS

With this review we have systematized the state of the art on the influence of speed in biomechanical parameters that characterize the gait action. Table 5 presents a synthesis of the consensual findings. However, other parameters seemed to be differently affected by gait speed in different studies, introducing a controversy that needs further contributions and deeper and extensive research.

TABLE 5 — Influence of gait speed on biomechanical variables.

	PLANTAR PRESSURE	KINETIC	KINEMATIC	EMG
Stride and step frequency	—	↑	↑	—
Stride and step length	—	↑	↑	—
Time duration of gait cycle	—	↓	↓	—
Time duration of stance	↓	↓	↓	—
Time duration of double support phase	—	↓	↓	—
Peak pressure	↑	—	—	—
Maximum force	↑	—	—	—
Vertical GRF first peak	—	↑	—	—
Vertical GRF second peak	—	↑	—	—
Vertical GRF intermediate minimum	—	↓	—	—
Time to vertical GRF first peak	—	↓	—	—
Time to vertical GRF second peak	—	↑	—	—
Time to vertical GRF intermediate minimum	—	↑	—	—

Vertical impulse	—	↓	—	—
Anterior-posterior GRF first peak	—	↑	—	—
Anterior-posterior GRF second peak	—	↑	—	—
Anterior-posterior impulse	—	↑	—	—
Peak moments	—	↑	—	—
Peak powers	—	↑	—	—
Mechanical work	—	↑	—	—
Centre of mass amplitudes	—	—	↑	—
Muscle activity	—	—	—	↑

Concluding, it can be stressed out that changing gait speed determines important changes in the human biomechanics of this particular locomotion action. A deeper knowledge of these changes may conduce to a better understanding of gait tests and normalization procedures, allowing a better evaluation capability of the gait pathological situations, as well as of the strategies to be implemented for its correction or compensation.

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