ISSN 2218-5836 (online)

World Journal of *Orthopedics*

World J Orthop 2017 November 18; 8(11): 815-852

Published by Baishideng Publishing Group Inc

WJO

World Journal of Orthopedics

A peer-reviewed, online, open-access journal of orthopedics

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2015-2018

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W J O

World Journal of
Orthopedics

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Monthly Volume 8 Number 11 November 18, 2017

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World Journal of Orthopedics is now indexed in Emerging Sources Citation Index (Web of Science), PubMed, PubMed Central and Scopus.

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NAME OF JOURNAL
World Journal of Orthopedics

ISSN
ISSN 2218-5836 (online)

LAUNCH DATE
November 18, 2010

FREQUENCY
Monthly

EDITORIAL OFFICE
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World Journal of Orthopedics
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7901 Stoneridge Drive, Suite 501, Pleasanton, CA 94588, USA
Telephone: +1-925-2238242
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E-mail: editorialoffice@wjgnet.com
Help Desk: http://www.f6publishing.com/helpdesk
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PUBLISHER
Baishideng Publishing Group Inc
7901 Stoneridge Drive,
Suite 501, Pleasanton, CA 94588, USA
Telephone: +1-925-2238242
Fax: +1-925-2238243
E-mail: bpgoffice@wjgnet.com
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PUBLICATION DATE
November 18, 2017

INSTRUCTIONS TO AUTHORS
http://www.wjgnet.com/bpg/gerinfo/204

ONLINE SUBMISSION
http://www.f6publishing.com

World Journal of Orthopedics

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World J Orthop 2017 November 18; 8(11): 815-828

DOI: 10.5312/wjo.v8.i11.815

ISSN 2218-5836 (online)

REVIEW

Balance control during gait initiation: State-of-the-art and research perspectives

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Author contributions: Yiou E, Caderby T, Delafontaine A, Fourcade P and Honeine JL participated in the writing of the paper and prepared the figures; Yiou E designed the outline and coordinated the paper.

Conflict-of-interest statement: There is no conflict of interest.

Manuscript source: Invited manuscript

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Received: June 9, 2017
Peer-review started: June 13, 2017
First decision: August 4, 2017
Revised: August 30, 2017
Accepted: September 12, 2017
Article in press: September 13, 2017
Published online: November 18, 2017

Abstract

It is well known that balance control is affected by aging, neurological and orthopedic conditions. Poor balance control during gait and postural maintenance are associated with disability, falls and increased mortality. Gait initiation - the transient period between the quiet standing posture and steady state walking - is a functional task that is classically used in the literature to investigate how the central nervous system (CNS) controls balance during a whole-body movement involving change in the base of support dimensions and center of mass progression. Understanding how the CNS in able-bodied subjects exerts this control during such a challenging task is a pre-requisite to identifying motor disorders in populations with specific impairments of the postural system. It may also provide clinicians with objective measures to assess the efficiency of rehabilitation programs and better target interventions according to individual impairments. The present review thus proposes a state-of-the-art analysis on: (1) the balance control mechanisms in play during gait initiation in able bodied subjects and in the case of some frail populations; and (2) the biomechanical parameters used in the literature to quantify dynamic stability during gait initiation. Balance control mechanisms reviewed in this article included anticipatory postural adjustments, stance leg stiffness, foot placement, lateral ankle strategy, swing foot strike pattern and vertical center of mass braking. Based on this review, the following viewpoints were put forward: (1) dynamic stability during gait initiation may share a principle of homeostatic regulation similar to most physiological variables, where separate mechanisms need to be coordinated to ensure stabilization of vital variables, and consequently; and (2) rehabilitation interventions which focus on separate or isolated components of posture, balance, or gait may limit the effectiveness of current clinical practices.

Key words: Balance control; Anticipatory postural adjustments; Leg stiffness; Foot placement; Lateral ankle strategy; Foot strike pattern; Vertical center of mass braking; Dynamic stability; Gait initiation; Biomechanics

Core tip: This review proposes a state-of-the-art on: (1) the balance control mechanisms in play during gait initiation in able bodied subjects and in the case of some frail populations; and (2) the biomechanical parameters used in the literature to quantify dynamic stability. The following viewpoints were put forward: (1) dynamic stability during gait initiation may share a principle of homeostatic regulation similar to most physiological variables, where separate mechanisms need to be coordinated to ensure stabilization of vital variables, and consequently; and (2) rehabilitation interventions which focus on separate or isolated components of posture, balance, or gait may limit the effectiveness of current clinical practices.

Yiou E, Caderby T, Delafontaine A, Fourcade P, Honeine JL. Balance control during gait initiation: State-of-the-art and research perspectives. *World J Orthop* 2017; 8(11): 815-828 Available from: URL: http://www.wjgnet.com/2218-5836/full/v8/i11/815.htm DOI: http://dx.doi.org/10.5312/wjo.v8.i11.815

INTRODUCTION

Gait initiation refers to the transient period between the quiet standing posture and steady state walking[1-5]. It is a functional task that is classically used in the literature to investigate how the central nervous system (CNS) controls balance during a whole-body movement involving change in the base of support dimensions and center of mass progression. Gait initiation is known to be a highly challenging task for the balance control system. Gait initiation indeed requires the integration of multiple sensory information arising from somatosensory, vestibular and visual systems, along with the coordination of multiple skeletal muscles distributed over the whole body. As such, it may potentially expose populations with sensory or motor deficits or disorders to the risk of fall[6-8]. Falls represent the second cause of mortality in the world, and one third of subjects over 65 years and 50% of those over 80 years living at home fall at least once a year[9]. Although being a very important issue gait analysis however received relatively little attention by orthopedic surgeons. This is particularly troublesome for understanding the pathogenesis of fractures, such as hip or wrist fractures, by those treating these highly frequent traumatic issues.

Understanding how the CNS in able-bodied subjects controls balance during such a challenging task is a pre-requisite to identifying motor disorders in populations with specific impairments of the postural system or fear of falling, such as the elderly or patients with neurological/orthopedics conditions. It may also provide the clinicians with objective measures to assess the efficiency of rehabilitation programs and to better target interventions according to individual impairments. Hence, beside a basic interest *per se*, it is therefore important to identify the different balance control mechanisms available to participants that ensure stabilization during whole-body progression. It is also important to define adequate biomechanical measures of stability to evaluate the efficiency of these mechanisms. Recent studies in the biomechanical field bring novel insights on these two aspects and open new research avenues, some of which will be mentioned in the present paper.

The present review thus proposes a state-of-the-art on: (1) the balance control mechanisms in play during gait initiation in able bodied subjects and in the case of some frail populations; and (2) the biomechanical parameters used in the literature to quantify postural stability during gait initiation. Before considering these aspects, let us first recall why balance is challenged during gait initiation.

BALANCE IS DISTURBED DURING GAIT INITIATION

During quiet standing, stability requires that the vertical projection of the center of mass falls within the base of support[10,11] (Figure 1). The center of mass corresponds to the point where the mass of the whole body is concentrated. It is the point of application of the gravity force vector. In the standing posture, the base of support refers to the area that includes every point of contact that the foot (or the feet) make(s) with the supporting surface. When one lifts the foot from the ground to step in the desired direction, balance is potentially challenged along the mediolateral direction because the base of support width in this direction is then drastically reduced. If the center of mass is not repositioned above the new base of support, a mediolateral gap between the center of mass and the center of pressure will be created. The center of pressure corresponds to the barycenter of the ground reaction forces. As a consequence of the mediolateral gap between the center of pressure and center of mass, the whole body will fall towards the swing leg side during the unipodal (or "execution") phase of gait initiation. The amplitude of this mediolateral fall can be estimated from the center of mass displacement

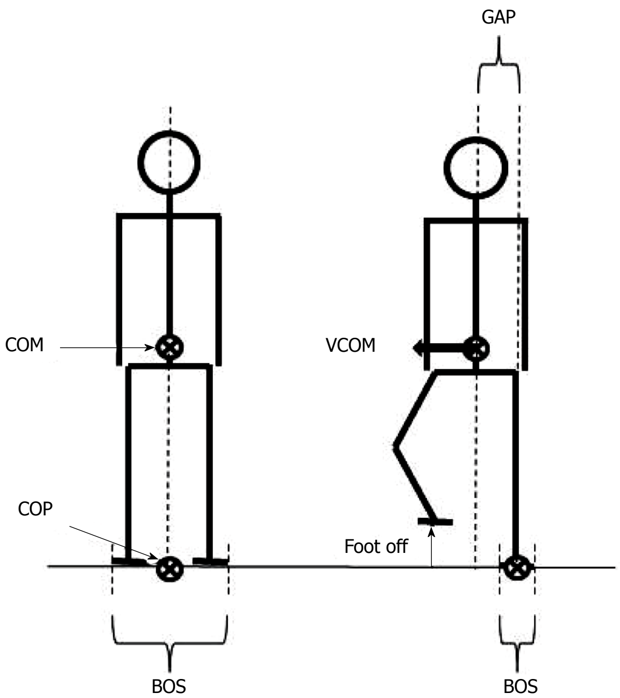

Figure 1 Representation of selected basic notions for balance analysis in biomechanics. Note that in the quiet standing posture (left figure), the vertical projection of the COM onto the ground falls on the COP. When the subject lifts the foot to step forward (right figure), the base of support size is drastically reduced. A gap between the COP and the COM may then occur, thus causing a disequilibrium towards the stance leg. COM: Center of mass; COP: Center of pressure; BOS: Base of support; VCOM: COM velocity.

and velocity at the time of swing foot contact, *i.e.*, the greater these two quantities, the larger the mediolateral fall[12-15].

Although a recent modelling study reported that an attenuation of this mediolateral fall may theoretically occur during the execution phase of gait initiation *via* an action on the stance leg stiffness[15] (cf. paragraph "stabilizing features of gait initiation"), this fall towards the swing leg side seems mainly to be braked by the swing foot landing. Swing foot landing indeed acts to provide an immediate enlargement of the base of support size so that the center of pressure may then be shifted laterally beyond the center of mass and thus create a counterbalancing torque oriented toward the stance leg side. Now, this lateral fall may be too significant to be braked by swing foot contact, *e.g.*, if the hip musculature of the swing leg becomes too weak to ensure this braking. This may be the case with aging or neurological/orthopedic conditions. In these cases, the center of mass may then be shifted laterally beyond the base of support with potential risk of the body falling onto the ground if appropriate actions are not undertaken.

It is noteworthy that such lateral falls are common in older adults and are associated with a 6-fold greater risk of hip fracture, compared with falls in other directions, *i.e.*, anterior and posterior falls (*e.g.*, Ref[16-19]). Deficits in the capacity to overcome the mediolateral perturbation to balance due to gravity force is thus thought to be of major importance in the aetiology of falls in frail populations[20,21].

Beside mediolateral instability, it is well known that the collision of the swing foot with the ground generates a large peak vertical ground reaction force. The amplitude of this peak may reach approximately twice body weight during barefoot walking at maximal speed (approximately 2 m/s). This peak, and probably most important, the slope of the vertical ground reaction force rise following the swing foot contact, may potentially cause discomfort or pain to body joints with task repetition (*e.g.*, Ref[22,23]). This perturbing effect is due to the transmission of the vibration from the swing foot to the whole body *via* bones and soft tissues. When walking with shoes at a normal speed (approximately 1.3 m/s) onto an unobstructed track, the amplitude of this vibration can easily be supported by any subject with either pathology or frailty. This may not be the case if participants have to clear a large obstacle (*e.g.*, Ref[15,24]), which may then increase the fall duration of the center of mass and therefore the vertical peak impact force and the associated slope. This perturbing effect may also be exacerbated if participants initiate gait barefoot and on a hard surface, if they descend large stairs, or if they suffer from knee joint pain or knee hypomobility, *e.g.*, due to the use of an orthosis or to pathology.

Knee joint mobility (flexion) *post* swing foot contact is known to play an important role in damping these vertical ground reaction forces (*e.g.*, Ref[25,26]). Mechanisms other than swing leg knee flexion are also developed in anticipation of swing foot contact. These mechanisms act in combination to attenuate these disturbing forces and thus avoid body collapse on the ground. As such, they also contribute to maintaining stability. These stabilizing mechanisms are described in the paragraph below.

To summarize, balance is disturbed during gait initiation because the act of lifting the swing foot from the ground induces a gap between the center of mass and the center of pressure. This gap is responsible for generating body disequilibrium and a fall towards the swing leg side. In addition, the collision of the swing foot with the ground generates a peak vertical ground reaction force which is transmitted from swing foot to the whole body *via* bones and soft tissues. These perturbations may be responsible of falls if not properly counterbalanced.

STABILIZING MECHANISMS INTO PLAY DURING GAIT INITIATION

Once the different sources of disturbance are identified, the question arises as to what the nature of the different mechanisms allowing able-bodied subjects to progress safely (*i.e.*, without falling) in the desired direction is.

Anticipatory postural adjustments

Gait initiation is classically divided in three successive

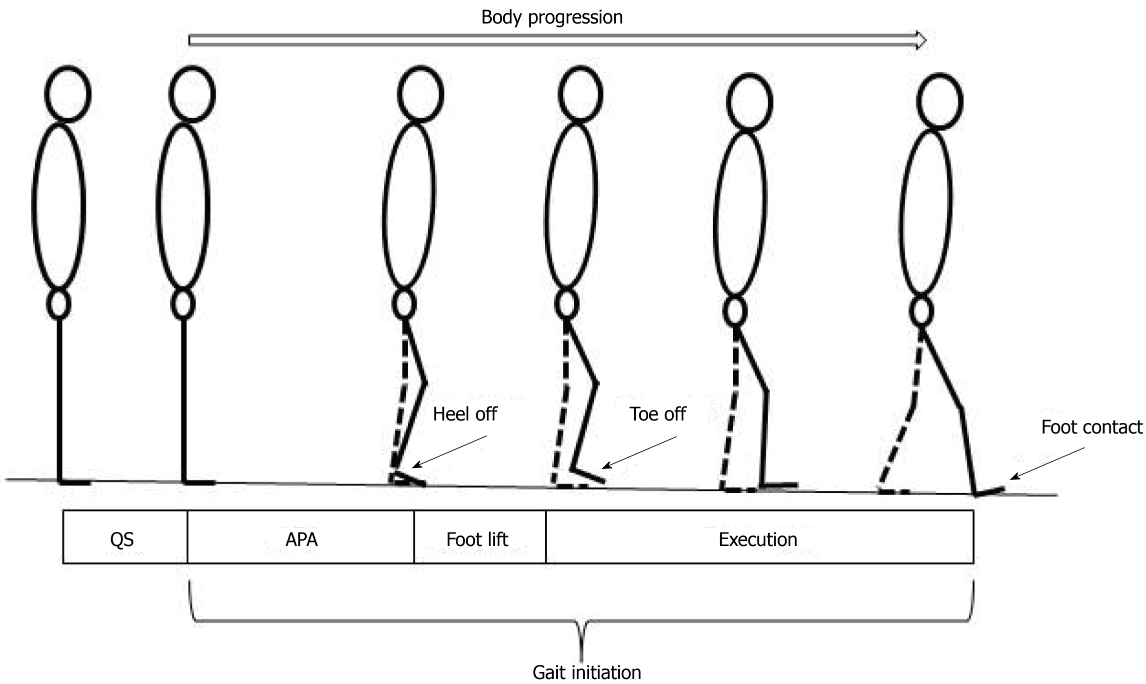

Figure 2 Stick representation of the different phases and temporal events of gait initiation. APA: Anticipatory postural adjustments.

phases: A postural phase which precedes the swing heel off (this phase corresponds to the so-called anticipatory postural adjustments, APAs, described in this paragraph), followed by the foot lift phase that ends at the time of swing toe clearance (the mass of the body is transferred to the stance leg during this phase), and an execution phase that ends at the time of swing foot contact with the supporting surface (Figures 2 and 3).

It is now well established that dynamical and electromyographical phenomena are developed during APAs. Their functional role depends on the axis considered. APAs along the anteroposterior axis are predictive of motor performance[2,27] while APAs along the mediolateral axis are predictive of postural stability[14,15,28-31].

Along the anteroposterior axis, APAs include a backward center of pressure shift which promotes the initial forward propulsive forces (prior to toe off) required to reach the intended motor performance, in terms of step length and progression velocity[2,27]. The anticipatory backward center of pressure shift is due to bilateral inhibition of the ankle plantar-flexors activity followed by activation of ankle dorsi-flexors[32,33].

Along the mediolateral axis, APAs include center of pressure shift toward the swing leg which promotes center of mass shift in the opposite direction, *i.e.*, towards the stance leg[15,24,31] (Figure 3). These mediolateral APAs thus reduce the gap between the center of mass and the center of pressure at the foot off time. This gap reduction attenuates the mediolateral fall of the center of mass toward the swing leg during the execution phase due to gravity[12,15,28,29] (cf. paragraph above).

The anticipatory mediolateral center of pressure shift has been classically attributed to the loading of the swing leg associated with the activation of swing leg hip adductors[1,11]. Recent studies further reported that, the stance knee and hip are slightly flexed during APAs[31,34], which acts to unload the ipsilateral leg and therefore complement the action of swing hip abductors. EMG analysis revealed that the flexion of the stance knee is favored by bilateral soleus silencing and a greater ipsilateral tibialis anterior activity with respect to contralateral activity, while stance hip flexion was associated with activation of the stance rectus femoris. It is to note that, due to biomechanical constraints, initiating gait from a wider stance decreases the effectiveness of hip abductor activity and increases the reliance on stance knee flexion and *vice versa*[31].

As a direct consequence of this muscle synergy, when mediolateral balance control is examined in patients suffering from motor problems during gait initiation, hip abduction, stance hip and knee flexion should be considered. Knee flexion control in the frontal plane during APAs could be inadequate in patients suffering from gait problems such as cerebral palsy, Parkinson's disease[35-39], stroke, amputees[40]. For instance, freezing of gait in Parkinsonian patients is associated with knee trembling[41-45]. Jacobs *et al*[46] found that during gait initiation, knee trembling causes multiple APAs that are observable as a right-left leg loading-unloading cycles (cf. also[47]). Interestingly, the alternating unloading and loading of the legs was accompanied by similar alternating activation and deactivation of right-left *tibialis anterior* (Figure 2 in Jacobs *et al*[46]). Therefore, knee trembling in Parkinsonian patients may be preventing them from correctly displacing their center of mass towards the stance leg and thus not allowing them to

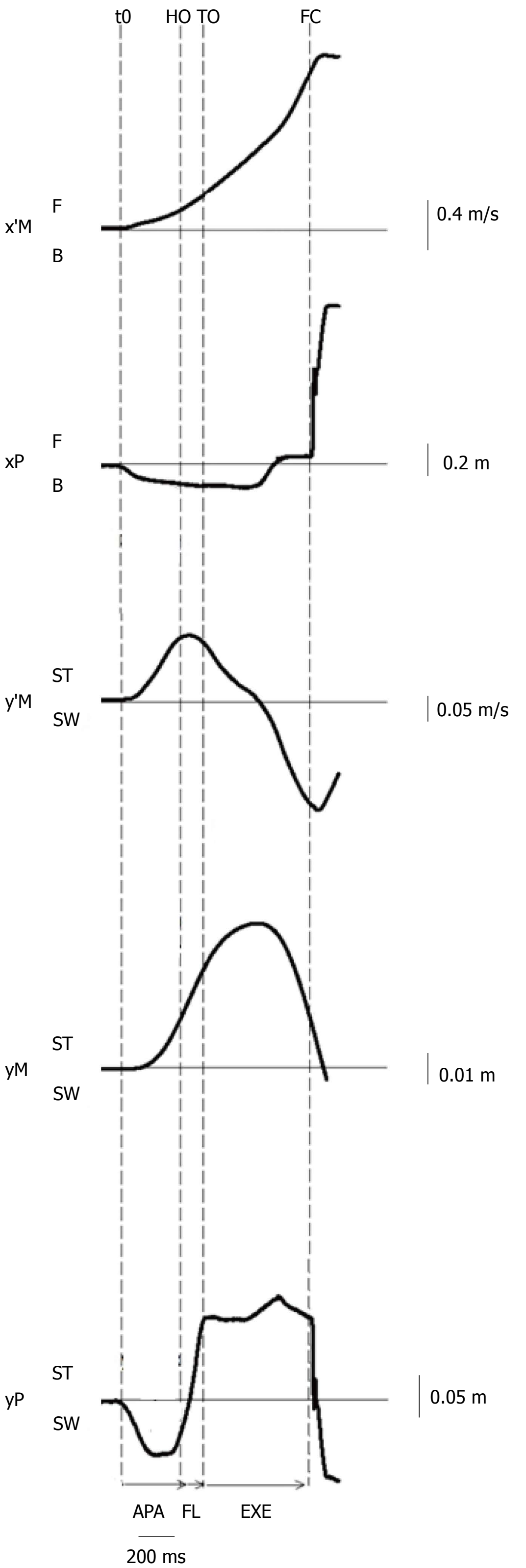

Figure 3 Example of biomechanical traces obtained for one representative subject initiating gait at a maximal velocity (one trial). Anteroposterior direction x'M: center of mass (COM) velocity; xP: Center of pressure (COP) displacement; F: Forward; B: Backward. Mediolateral direction y'M: Mediolateral COM velocity; yM: Mediolateral COM displacement; yP: Mediolateral COP displacement; ST: Stance limb; SW: Swing limb. Vertical dashed lines: t0 onset variation of biomechanical traces; HO: Swing heel off; FO: Swing foot off; FC: Swing foot contact. Horizontal arrows: APA: Anticipatory postural adjustments; FL: Foot lift; EXE: Execution phase.

initiate gait properly. Indeed, the smaller mediolateral center of pressure displacement during APAs and larger step width of the first step at gait initiation have been observed in Parkinson's disease[37,38]. This could be in part associated to inappropriate knee flexion. Therefore, it has been proposed by Honeine *et al*[31] that correcting the knee flexion angle of the stance leg during APAs with a smart orthosis could be an effective solution to enhance gait initiation and possibly steady-state gait in such patients. Future studies should investigate this aspect.

To summarize, lifting the swing foot for stepping forward induces a potential lateral body imbalance. This imbalance is partly countered is advance before swing foot off, *i.e.*, during APA. This APA includes center of pressure shift towards the swing leg which act to move the center of mass towards the stance leg. This lateral postural dynamics is due to motor synergy involving swing hip adduction, combined with stance knee and stance hip flexion. Deficits in this motor synergy with aging or pathology may increase the risk of imbalance.

Stance leg stiffness

To investigate the link between mediolateral APAs and postural stability during the execution phase of gait initiation (from toe off to foot contact), a recent study[15] modeled the human body as a single conic inverted pendulum which rotates about a fixed point (Figure 4).

This model was based on work carried out in earlier studies[3,12,13,48]. During the execution phase, it was considered that the center of mass was falling laterally under the influence of two forces: The gravity force P = mg (where m is the mass of the solid, and g is the gravitational acceleration) and an elastic restoring force T that reflects active muscular control of movement[49,50], with T = k|yM| (where k is the stiffness of the stance leg muscles during the execution phase[11] and |yM| is the absolute value of the mediolateral center of mass shift, which was systematically oriented towards the swing leg (positive values) during the execution phase. The initial position and velocity of the cone corresponds to the position and velocity of the subject's center of mass at toe off. The addition of a restoring force on the conic model was necessary in order to control the initial velocity at toe off. A visual analysis of Figure 2 illustrates the excellent fit between the experimental traces obtained during gait initiation and those obtained with the mechanical model. The best fit between experimental (dashed line) and theoretical (full line) data was obtained for stance leg stiffness in the frontal plane of about 1000 N/m. This corresponded to a restoring force of approximately T = 50 N, applied at the center of mass of the participant.

The results obtained in this latter study[15] suggested that changing the stance leg stiffness during the execution phase of gait initiation has the potential to influence the amplitude of the mediolateral fall of the center of mass. Stance leg stiffness can theoretically be modified by changing the co-activation level of agonistic/

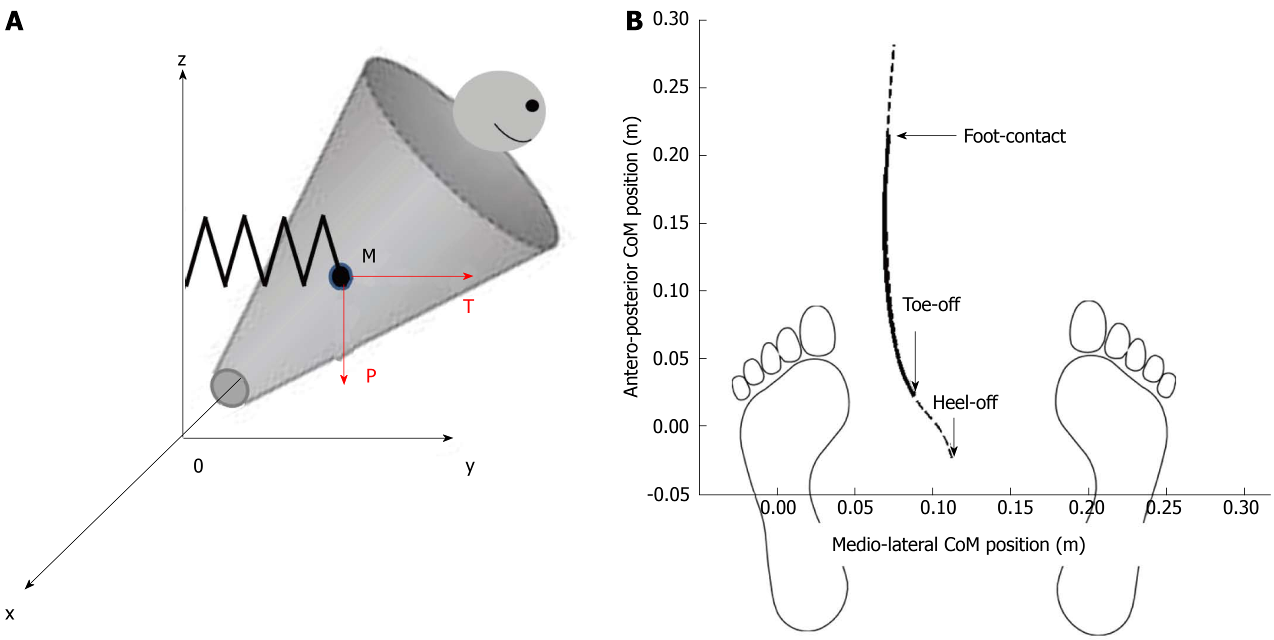

Figure 4 Mechanical model of the body during the execution phase of gait initiation. A: The mechanical model is represented as conic inverted pendulum which pivots around fixed point 0. Body displacement presents five degrees of freedom. The center of mass M falls under the influence of the gravity force "P" and the elastic restoring force "T"; B: Anteroposterior vs mediolateral path of the center of gravity. Dash line represents experimental data during the whole trial and full line represents theoretical data during the execution phase of gait initiation. Note the excellent fitting between these two traces.

antagonistic pairs of muscles crossing the ankle, knee or hip joints. Whether the global mediolateral leg stiffness is equally sensitive to co-activation of the muscles groups crossing each of these joints remains to be investigated. Whether the CNS uses this theoretical leg stiffness tuning strategy in combination with mediolateral APAs in order to attenuate the fall of the center of mass during gait initiation, and whether the use of this strategy depends on the sensorimotor state of the postural system also remain unanswered.

Interestingly, an increase in leg stiffness is commonly found in many neurological patients such as patients with Parkinson's disease, multiple sclerosis, stroke, *etc*. Based on this mechanical model, it can be speculated that part of the unstable state that is classically observed in these populations during gait initiation can be ascribed to an increase in stance leg stiffness. Besides, the use of medical devices such as leg orthoses, prostheses, plaster, *etc*. may also be expected to modify stance leg stiffness. On this aspect, Delafontaine *et al*[51] showed that wearing an orthosis over the ankle of the stance leg induced an increase in the mediolateral fall of the center of mass. In contrast, unpublished observations from our laboratory showed that wearing an orthosis over the knee of the stance leg did not induced any change in the mediolateral fall of the center of mass. These findings suggest that stance leg stiffness in the frontal plane may not be equally sensitive to ankle or knee stiffness. Future studies should investigate this aspect.

To summarize, stance leg stiffness during the execution phase of gait initiation may theoretically influence the mediolateral fall of the center of mass. It can thus be speculated that the increased leg stiffness in neurological patients such as patients with Parkinson's disease, multiple sclerosis, stroke, *etc*., or in patients wearing a leg orthosis, may be responsible of part of their unstable state.

Foot placement and lateral ankle strategy

Although modulations of both the mediolateral APAs and the stance leg stiffness may influence the extent to which the center of mass falls toward the swing leg during step execution, it is known that these mechanisms do not fully stabilize the whole-body in the frontal plane during gait initiation[3,12,14,15]. Yet, mediolateral stability must necessarily be restored in order to ensure safe forward progression. It is acknowledged that the primary mechanism employed to restore stability in the frontal plane following the swing foot off is the foot placement[48,52,53]. As stated above, the action of repositioning the swing foot onto the ground allows to enlarge the base of support and opens the possibility of displacing laterally the center of pressure beyond the center of mass. In this way, it becomes possible to create a mediolateral gap between the center of mass and the center of pressure that will brake the lateral body fall and accelerate the center of mass in the direction of the stance leg (Figure 5).

Results from the literature reveal that the foot placement is actively regulated by the CNS to restore and control balance in the mediolateral direction[54-57]. Foot placement would be mainly adjusted by the activity of the hip abductors of the swing limb in response to the mechanical state of the body, in terms of center of mass position and velocity[58,59]. Interestingly, Caderby *et al*[60] have investigated the effect of the progression

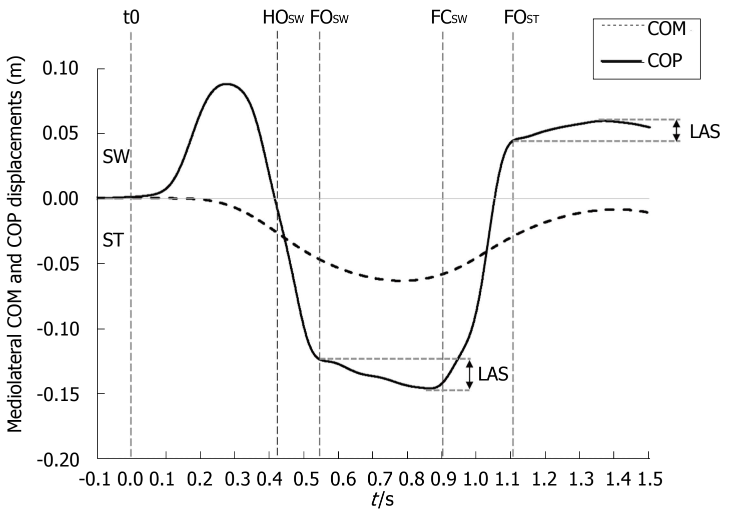

Figure 5 Typical time course of the center of mass and the center of pressure along the mediolateral direction during gait initiation. The traces were obtained for one subject initiating gait at self-selected speed (one trial). SW and ST indicate swing limb and stance limb, respectively. t0, HOSW, FOSW, FCSW, FOST: Onset variation of biomechanical traces, swing heel-off, swing foot off, swing foot contact, stance foot off, respectively. LAS indicates "lateral ankle strategy". The extent of the corrections achievable by this strategy may be appreciated by the difference between both the initial and the maximum lateral positions of the COP during the single support phase. COM: Center of mass; COP: Center of pressure.

velocity on the mediolateral stability control during gait initiation. These authors noted that when participants initiated gait at high speed, the lateral fall of the center of mass toward the swing limb during step execution was increased compared with gait initiation performed at low and normal speeds. Nevertheless, it was observed that the participants were able to compensate this higher mediolateral instability in the high speed condition by enlarging the step width (*i.e.*, the base of support) such that the mediolateral dynamic stability at the time of foot contact remained unchanged. These findings underlined that healthy young adults were able to finely tune the mediolateral foot placement such as to maintain an invariant mediolateral stability during gait initiation. Results obtained during steady state walking indicate that the accuracy of the foot placement may be altered in patients suffering from sensory and motor impairments. Specifically, it has been observed that above-knee amputees[58] and patients with stroke[61] exhibited a reduced ability to appropriately control foot placement, which may consequently contribute to a higher lateral instability.

It is worth noting that small errors in the foot placement may be corrected even after foot landing. Indeed, after the swing foot is positioned onto the ground, it remains possible to adjust the mediolateral position of the center of pressure located beneath this foot (Figure 5). This mechanism, called "lateral ankle strategy", would be mainly controlled by the ankle inversor/eversor muscles of the supporting foot[58,62]. Although the extent of the corrections achievable by this mechanism is small, as it is limited by the width of the foot, it allows a fine-tuning of the torque induced by the mediolateral gap between the center of pressure and the center of mass that acts to brake the lateral fall of the body. During steady state walking, Hof *et al*[58] have shown that the range of corrections attainable by this mechanism was reduced in above-knee amputees for their prosthetic leg (1-2 cm) compared with their sound leg (1.7-4.4 cm) and compared with healthy subjects (0.7-3 cm). These findings suggest that this mechanism could also be altered in people suffering from sensorimotor problems.

Reinmann *et al*[63] advanced that foot placement and lateral ankle strategy may be two independent mechanisms that are likely coupled and temporally coordinated. What the relative importance of each mechanism is in balance maintenance and how they are coordinated in normal subjects and in patients with postural disorders are questions that remain to be elucidated.

To summarize, lateral swing foot placement and lateral ankle strategy are two independent mechanisms that are likely coupled and temporally coordinated. These mechanisms may complement the mediolateral APAs and stance leg stiffness regulation to stabilize the whole-body in the frontal plane[64-67].

Vertical center of mass braking

As stated above, during the execution phase of gait initiation, the backward center of pressure shift that is generated during APAs propels the center of mass away from the base of support[27,68]. The distance between the center of mass and the center of pressure allows gravity to generate a disequilibrium torque which accelerates the center of gravity in both the anterior and downward directions[11]. Consequently, the lowest center of mass position throughout gait initiation is measured at the instant of foot contact. Nonetheless, in healthy adults, the center of mass velocity reaches a maximum absolute value around mid-single stance and then is decreased (Figure 6). This center of mass

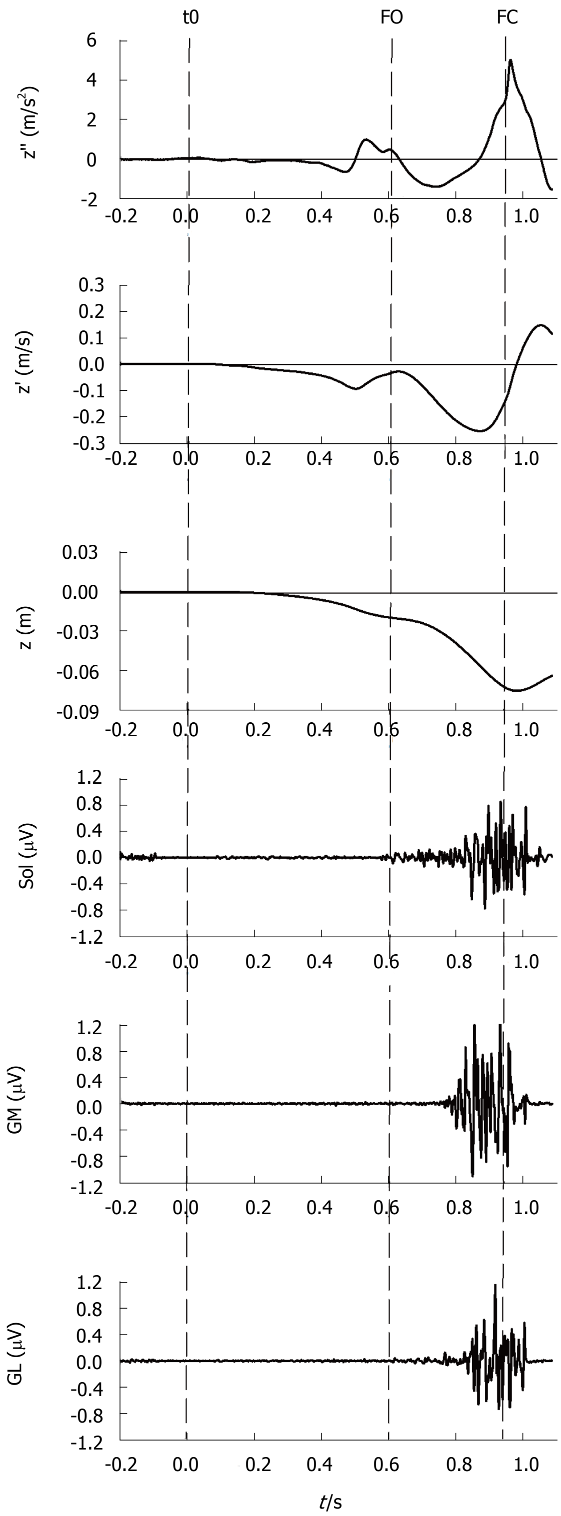

Figure 6 Vertical braking of center of mass during gait initiation. This figure shows, from top to bottom, the timelines of the COM vertical acceleration (z''), COM vertical velocity (z'), COM vertical position (z) as well as the electromyographical activity of stance leg triceps surae activity, *i.e.*, soleus (Sol), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL) of a single recording during gait initiation. The dashed lines indicate the instants of initiation (t0), foot off (FO) and foot contact (FC). As can be seen in the figure, step execution is accompanied by a downward (negative) COM acceleration. During mid-single stance, triceps surae activity counteracts gravity and brakes the vertical fall of COM. The braking action of COM is observable as a positive acceleration (top panel) which causes the vertical absolute velocity at foot contact to be lower than the peak absolute velocity measured in mid-single stance. COM: Center of mass.

vertical deceleration has been shown to result from the increase in *triceps surae* activity that occurs during the second half of the execution phase of gait initiation[69].

By counteracting gravity, the triceps surae also plays a role in modulating the disequilibrium torque and setting velocity and duration of step execution as well as step length[70]. On the one hand, it has been argued that the braking action limits the amplitude of the impact of the swinging leg with the ground at foot contact[71,72]. On the other hand, Kuo[73] reasoned that the vertical force produced during late single-stance decreases the work needed to raise the center of gravity in the ensuing double stance phase. Consistent with this hypothesis, Bregman *et al*[74] showed that the spring assistive ankle foot-orthosis decreases the energetic cost of hemiplegic patients by 10% during double support.

The active braking of the center of mass during step execution is not observed before the age of 4[75]. This implies that active braking requires a process of neural learning[76-78]. In addition, progressive supranuclear palsy[72] and Parkinson patients[79,80] as well as elderly people[81] have all been found to have difficulties in decelerating the center of mass' downward velocity. The dysfunction in the braking action of center of mass has been linked to lesion or dysfunction of the network linking the primary motor cortex and the mesencephalic locomotor region which is involved in the control of gait and balance[82]. Furthermore, induced ankle joint mobility on healthy individuals has also been shown to play a role in modulating the active braking of center of mass[51,83]. In those studies, the modifications in the proprioceptive inputs, due to strapping the ankle joint or by wearing a rigid ankle foot orthosis, are likely the cause of the deterioration in vertical braking. While proprioception has been shown to play a role in modulating the APAs phase of gait[84-86], more research is needed to understand how somatosensory inputs are integrated in order to generate the central commands responsible for the vertical braking action on center of mass.

To summarize, the center of mass' downward velocity is actively braked during step execution thanks to the activation of the triceps surae of the stance leg. Difficulties to perform this active vertical braking, as observed in patient with progressive supranuclear palsy and with Parkinson disease as well as in elderly people, may induce postural instability.

Swing foot strike pattern

During locomotion, it is known that the collision of the swing foot with the ground can occur in three ways (*e.g.*, Ref[22,23]): A rear foot strike, in which the heel lands first; a mid-foot strike, in which the heel and ball of the foot land simultaneously; and a fore foot strike, in which the ball of the foot lands before the heel comes down. During running, the strike patterns vary within subjects and whether participants are shod or barefoot. Kinematic and kinetic analyses showed that even on hard surfaces, barefoot runners who fore-foot strike

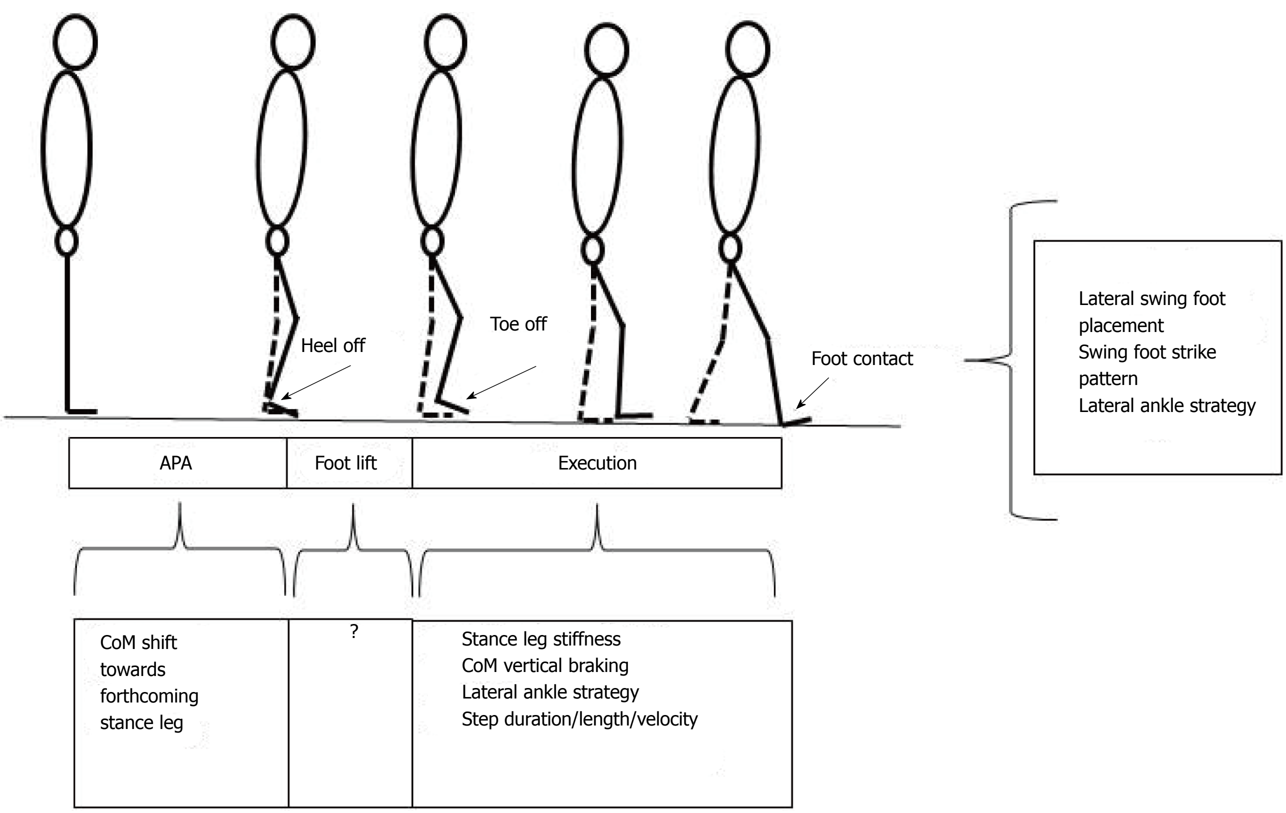

Figure 7 Synthesis of balance control mechanisms into play during gait initiation. The coordination between these different mechanisms remains to be elucidated.

generate smaller collision forces than shod rear-foot strikers[23]. This difference results primarily from a more plantar-flexed foot at landing and more compliance during impact, decreasing the effective mass of the body that collides with the ground. To date, in most studies on gait initiation, participants initiate gait unshod on an unobstructed track and over the hard surface of a force plate. In these classical conditions, participants spontaneously use a rear foot strike whatever the progression velocity. Recent study[15] however reported that when participants initiate gait at maximal velocity with the instruction to clear an obstacle, the percentage of fore-foot strike progressively increased with the obstacle distance, passing from 8% for obstacle at 10% of body height to 21% for obstacle at 30% of body height. Forefoot strike was also reported in young healthy adults during stairs descend[64]. The question of how the CNS in young healthy adults *vs* frail subjects with high risk of fall coordinates their foot strike pattern with the strategy of active braking of the vertical center of mass fall (cf. paragraph above), remains to be explored in both walking and running. Impairment in the coordination between these two strategies of vertical ground reaction force damping may potentially increase the risk of injuries (*e.g.*, tibial stress fractures[65,66] and plantar fasciitis[67]) and/or of body collapse on the ground. This research avenue is currently under investigation in our laboratory.

To summarize, the swing foot strike pattern used by participants during locomotion (rear foot, mid-foot, or fore foot strike pattern) influences the damping of the ground impact force. Swing foot strike pattern may be combined with active vertical braking of the center of mass to attenuate the potentially damaging effects of the collision forces generated at the time of foot contact.

The different balance control mechanisms at play during gait initiation are summarized in the Figure 7.

MEASURING DYNAMIC STABILITY DURING GAIT INITIATION

As stated above, the condition for stability during quiet standing holds that the vertical projection of the center of mass falls within the base of support[10,11]. As stressed in the literature, this condition is sufficient during quiet standing when the velocity of the center of mass can be neglected. However, during dynamical tasks such as gait initiation, the velocity of the center of mass cannot be neglected and this quantity has to be taken into consideration in the condition for stability[87,88]. To illustrate this necessity, Hof *et al*[87] emphasized "that even if the center of mass is above the base of support, balance may be impossible if the center of mass velocity is directed outward. The reverse is also possible: Even if the center of mass is outside the base of support, but its velocity directed towards it, balance can be achieved". The former situation is particularly relevant to the gait initiation process where the center of mass position falls normally within the base of support at the time of foot contact while its velocity is then directed outwards, *i.e.*, towards the swing leg side.

Until recently, authors compared stability across stepping task conditions with measures of mediolateral center of mass shift, velocity and step width at the time of swing foot contact (*e.g.*, Ref[12,14,29,89,90]). It was assumed that the lower these kinematical center of mass variables are and the larger the step width, the greater the stability. These variables were however considered separately, which made comparison of stability across conditions potentially difficult. Difficulty would indeed arise in a situation where the base of support size is increased, thus yielding a greater stability, and where the center of mass velocity or shift at swing foot contact is also increased, thus yielding a lower stability: It could not be clearly determine whether stability is improved or not.

Hof *et al*[87] proposed an extension of the classical condition for stability in static situations to dynamical situations where the position of the vertical projection of the center of mass plus its velocity times a factor (square root L/g) should fall within the base of support, l being leg length and g the acceleration of gravity. These authors suggested naming this vector quantity "extrapolated centre of mass position", because the centre of mass trajectory is extrapolated in the direction of its velocity. According to these authors, the definition put forward the "margin of stability", which was defined as the minimum distance from extrapolated centre of mass position to the boundaries of the base of support, as a measure of dynamical stability. The margin of stability can thus be considered as a "synthetic" variable since it simultaneously takes into account the position of the center of mass, its velocity and the base of support size. Since the publication of Hof *et al*[87], this quantity is increasingly used in the literature to quantify stability during dynamical tasks such as steady-state locomotion[21,91,92], gait initiation[15,24,60,93], leg flexion[20,94], sit-to-stand[95], *etc.*

To summarize, the condition for dynamic stability holds that the position of the vertical projection of a quantity termed the "extrapolated center of mass" should fall within the base of support. The distance between the boundaries of the base of support and the extrapolated center of mass (*i.e.*, "the margin of stability") is increasingly used in the literature to quantify stability during dynamical tasks.

STABILITY-RELATED CONTROLLED VARIABLES

The mediolateral margin of stability was fruitfully used in recent studies which investigated the adaptability of the stabilizing features of various stepping tasks (gait initiation, rapid leg flexion or abduction) to spatial or temporal constraints imposed on the postural system in young healthy adults and seniors. These constraints included temporal pressure[15,20,24,94], obstacle clearance[15,24], fear of falling[96-98], velocity instruction[60], and symmetrical or asymmetrical body loading[93,99]. In brief, these studies have repeatedly shown that participants were able to develop adaptive postural strategies in the forms of changes in the APAs' spatio-temporal features, step width and/or swing foot strike pattern (cf. paragraph above) so as to maintain an invariant margin of stability value across the different conditions. A recent study using mechanical modeling of the human body during gait initiation over obstacles of varying heights and distances (cf. paragraph Stance leg stiffness) reinforced this idea of adaptive stabilizing features by showing that a negative value of the margin of stability at foot contact would occur (thus yielding an instable state) should these changes not be developed[15]. This invariance of the margin of stability under various postural constraints led authors to suggest that this quantity may function as a possible balance control parameter during gait initiation.

As a marked exception, unpublished data obtained in twenty seven healthy young adults showed that unilateral knee joint hypomobility experimentally induced by the wear of an orthosis over the stance or the swing leg induced an increased margin of stability compared to unconstrained gait initiation, thus yielding a more stable state. This result was due to an enlarged step width in the conditions with an orthosis. In addition, participants spontaneously initiated gait with a smaller step length and reduced progression velocity, which allowed them to maintain an invariant peak vertical ground reaction force and associated slope values. This statement was strengthened by the result that participants were in fact able to reach the same step length and progression velocity when instructed to do so. But, in this case, the slope (and to a lesser extent, the peak vertical ground reaction force) was then largely increased compared to the control condition. As an expected consequence, participants reported discomfort at the heel, knee and hip with repetition.

To summarize, these results showed that when a mechanical constraint is applied to the leg, the CNS uses a more protective strategy by giving priority to stability and joint comfort rather than to motor performance. It can thus be proposed that the CNS set reference values for stability and vertical disturbance before stepping. The CNS would then plan the stabilizing features and motor performance of gait initiation so as to reach these desired reference values. These references values may change according to the instructions given to participants and the sensorimotor state of the locomotor apparatus.

CONCLUSION

The findings reported in this review may be replaced in the broader framework of homeostasis in Physiology[100]. According to the definition, homeostasis is the tendency of a system, especially the physiological system of higher animals, to maintain internal stability, owing to the coordinated response of its parts to any situation or stimulus that would tend to disturb its normal condition or function. During gait initiation, the regulation of dynamic stability and vertical disturbance at foot collision seems to respond to this definition. Results reported in this review indeed showed that in situations where instability and vertical disturbance may potentially be increased due to internal or external constraints, a compound of postural responses are triggered that allows to keep these biomechanical variables constant. It was thus proposed that the CNS sets reference values to be kept invariant before stepping and that balance control mechanisms would be planned accordingly. In the physiological domain, reference values are also supposed to be set by the CNS for controlled variables such as the neuromuscular spindles sensitivity, glycemia, blood pressure, natremia, *etc*. As for the maintenance of dynamic stability during gait initiation, the maintenance of these physiological variables requires both anticipatory and reactive mechanisms (cf. for example the anticipatory secretion of insulin before glycemia rises). This review advances the viewpoint that dynamic stability during gait initiation (as measured with the margin of stability) may share a similar principle of functional regulation. Now, the question how these different balance control mechanisms are coordinated to ensure the regulation of dynamic stability remains to be clarified. Specifically, to what extent these mechanisms are complementary and may substitute to each other in case of motor deficiency should be investigated in future studies. This knowledge is important for the clinician to better understand the pathophysiology of balance disorders with aging, neurological and orthopedic conditions. Thus, this review further advances the viewpoint that rehabilitation interventions focused on separate or isolated components of posture, balance, or gait may limit the effectiveness of current clinical practices.

ACKNOWLEDGMENTS

The authors would like to thank Dr. David Gibas for editing and proofreading the final version of the manuscript.

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P- Reviewer: Angoules A, Emara KM, Guerado E, Papachristou GC, Peng BG, Rothschild BM, Unver B **S- Editor**: Ji FF
L- Editor: A **E- Editor**: Lu YJ

WJO World Journal of Orthopedics

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World J Orthop 2017 November 18; 8(11): 829-835

DOI: 10.5312/wjo.v8.i11.829

ISSN 2218-5836 (online)

ORIGINAL ARTICLE

Basic Study

Biomechanical assessment of new surgical method instead of kyphoplasty to improve the mechanical behavior of the vertebra: Micro finite element study

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Author contributions: Hosseini Faradonbeh SA and Jamshidi N substantially contributed to the conception and design of the study, acquisition, analysis and interpretation of data; all authors drafted the article and made critical revisions related to the intellectual content of the manuscript, and approved the final version of the article to be published.

Institutional review board statement: The study was approved by the head of animal care center at Department of Biomedical Engineering at the University of Isfahan.

Institutional animal care and use committee statement: The fresh ovine vertebrae were harvested from the dead sheep Carcasses without meaning any harm or pain to the living animals; approved by the University of Isfahan's Animal Care Committee at the time of adoption.

Conflict-of-interest statement: To the best of our knowledge no conflict of interest exists.

Data sharing statement: No additional data are available.

Manuscript source: Unsolicited manuscript

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Received: March 7, 2017
Peer-review started: March 10, 2017
First decision: June 30, 2017
Revised: July 5, 2017
Accepted: September 12, 2017
Article in press: September 13, 2017
Published online: November 18, 2017

Abstract

AIM

To reduce post treatments of kyphoplasty, as a common treatment for osteoporotic vertebrae.

METHODS

This study suggests a new method for treating vertebrae by setting the hexagonal porous structure instead of the rigid bone cement mass in the kyphoplasty (KP). The KP procedure was performed on the fresh ovine vertebra of the level L1. Micro finite element modeling was performed based on micro computed tomography of ovine trabecular cube. The hexagonal porous structure was set on one cube instead of the bone cement mass. For the implant designing, two geometrical parameters were considered: Spacing diameter and thickness.

RESULTS

The results of micro finite element analyses indicated the improvement in the mechanical behavior of the vertebra treated by the hexagonal porous structures, as compared to those treated by vertebroplasty (VP) and KP under static loading. The improvement in the mechanical behavior of the vertebra, was observed as 54% decrease in the amount of maximum Von Misses stress (improvement of stress distribution), in trabecular cube with embedded hexagonal structure, as compared to VP and KP. This is comparable to the results of the experimental study already performed; it was shown that the improvement of mechanical behavior of the vertebra was observed as: 83% increase in the range of displacements before getting to the ultimate strength (increasing the toughness) after setting hexagonal pearls inside vertebrae. Both the material and geometry of implant influenced the amount of Von Mises stress in the structure.

CONCLUSION

The new proposed method can be offered as a substitute for the KP. The implant geometry had a more obvious effect on the amount of Von Mises stress, as compared to the implant material.

Key words: Vertebroplasty; Kyphoplasty; Micro finite element modeling; Hexagonal porous structure; Von mises stress

Core tip: By embedding the hexagonal porous structure with two variable parameters including spacing diameter and thickness, as a substitute for the bone cement mass in the vertebral kyphoplasty, lower levels of maximum Von Mises stress could be achieved, thereby indicating the reduction of stress concentration in the interface area between the bone cement mass and the cancellous bone, as well as the reduction of post treatments. Furthermore, setting porous structures with different geometries inside vertebrae could provide the possibility of bone regeneration, the transfer of growth factors and recreation of mechanical properties.

Hosseini Faradonbeh SA, Jamshidi N. Biomechanical assessment of new surgical method instead of kyphoplasty to improve the mechanical behavior of the vertebra: Micro finite element study. *World J Orthop* 2017; 8(11): 829-835 Available from: URL: http://www.wjgnet.com/2218-5836/full/v8/i11/829.htm DOI: http://dx.doi.org/10.5312/wjo.v8.i11.829

INTRODUCTION

Vertebroplasty (VP) and kyphoplasty (KP) as minimally invasive surgeries, consume poly methyl methacrylate (PMMA) and calcium phosphate as the bone cement for the treatment of patients with osteoporotic disorders in vertebral column. But one important challenge affecting the quality of procedure is the leakage of bone cement. Also the mechanical behavior of treated vertebra can affect biomechanics of the whole spine[1-3]. It is known that the KP does not guarantee the stoppage of fractures. Based on the studies of Polikeit *et al*[4], the strength of the treated vertebrae can be regained by cement augmentation, while it increases the endplate bulge and generates some altered load transfer in adjacent vertebrae. Then the rigid cement augmentation could facilitate the subsequent collapse of adjacent vertebrae.

According to a careful literature review performed by Wilcox[5], the main factors affecting the spine performance after cement augmentation can be classified in three groups: (1) the cement properties and volume; (2) the features of connection between the structure and vertebra; and (3) the spine properties. The bone and cement interface is important in providing the longer term stability of the construction. Cement augmentation improves motion segment stiffness, while, it alters the bone stress distributions in the treated and adjacent segments.

Keller *et al*[6], indicated that cement injection affects the stress distribution in both the vertebra and adjacent segments. Rohlmann *et al*[7] proved that the wedge shaped vertebral body could alter the center of the gravity of the upper body. This shift was compensated by the KP leading to a lower muscle force and an increase in the spinal load. The cement augmentation increases the intradiscal pressure in adjacent discs with a slight increase in Von Mises stress in vertebral endplates. Based on attempts of Liang *et al*[8], the asymmetrical cement distribution inside the treated vertebra led to the unrelieved pain after percutaneous vertebral augmentation. The insufficient distribution of the bone cement increased the displacement of augmented vertebral body. Tschirhart *et al*[9] and Xu *et al*[10], both emphasized that in the case of severe fractures, cement augmentation could worsen the fracture, leading to the cement leakage with subsequent problems; this indicated the uncertainty in the results of VP. Baroud *et al*[11], emphasized that both experimental study and finite element modeling are often focused on the effect of type of bone cement and volume. To reduce the risk of adjacent fracture after cement augmentation, Boger *et al*[12] suggested consuming the low modulus cement (consisting of the regular bone cement (PMMA) and the low-modulus cement prepared with Vertecem by the addition of an aqueous fraction of 35% sodium hyaluronate).

Kinzl *et al*[13], emphasized that stress concentration in trabecular bone is based on cement distribution. Basically, in the KP, the bone cement and trabecular structure are separated. So the whole structure is not homogeneous and the stress concentration can be seen in the interface area which is the reason of occurring micro fractures. The result of studies of Kosmopoulos *et al*[14] and Kettler *et al*[15], indicated that the main problems with the cement augmentation are: (1) stress concentration in the interface area; and (2) asymmetrical cement distribution. Baroud *et al*[16], proved that the wedge shaped vertebrae, induced a shift in the center of gravity of the upper body and therefore increased the intradiscal pressure and stress on endplates. Compensation of this shift by the

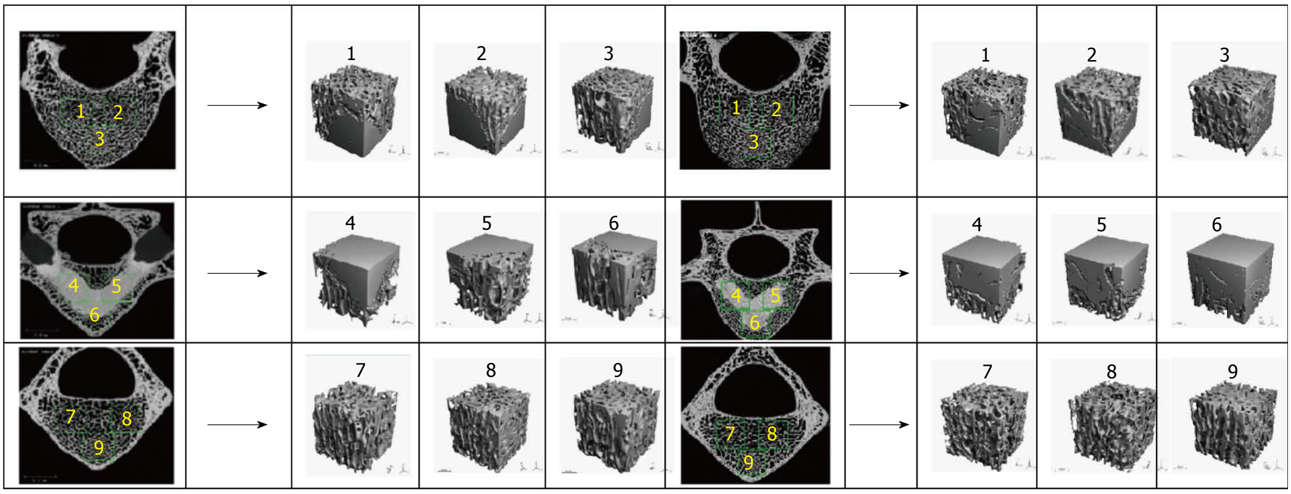

Figure 1 Subdividing the specimens of vertebroplasty (left) and kyphoplasty (right) to 9 smaller cubes in 3 layers in order to evaluate the regional variations in stress distribution.

KP procedure decreased the erector spinae force and also, the axial force in spinal column. Armsen *et al*[17], emphasized that in the case of the long term stability of the structure build up from the bone cement and trabecular bone, two main factors must be considered. First, it should be noted that the cytotoxicity of poly methyl methacrylate prevents the osteointegration; second, the osteoporosis as a progressive disease weakens the structure of the trabecular bone. Considering the necessity of setting a structure to solve mentioned problems, Garzón-Alvarado *et al*[18], suggested setting porous structures. Verhulp *et al*[19], emphasized that the structural complexity in trabecular bone could be the reason of existence of a wide range of differences in the amount of Von Misses stress in the structure. Landgraft *et al*[20], attempted to simulate the generation of microstructural models of human trabecular bone and the acrylic bone cement injection with the Finite Element Method (FEM) of cement curing inside vertebrae based on micro computed tomography (μCT) scanning.

Considering the results of all studies conducted to address the limitations of cement augmentation and the problems that patients may encounter after the VP and KP, the main drawbacks of these procedures can be classified as: (1) asymmetrical cement distribution inside the vertebra; (2) stress concentration in the interface area between cement mass and bone in the KP; (3) the risk of occurring fractures in the adjacent vertebrae; (4) the risk of cement leakage while augmenting; and (5) as an important case, different outcomes of patients due to ignoring the morphological parameters of trabecular bone such as trabecular thickness (Tb. Th) and trabecular spacing (Tb. Sp) in treating osteoporotic vertebrae.

In this study, the hexagonal porous structure with the low rate of mass/volume and high stability, is presented with defined geometrical parameters including thickness and spacing diameter, as determining factors to build the implant with optimum design and therefore, to reduce post treatments. Furthermore, setting porous structures with different geometries inside the vertebra, could provide the possibility of tissue regeneration, the transfer of growth factors and the recreation of mechanical properties.

MATERIALS AND METHODS

Preparation of specimens

Two L1 ovine vertebral bodies were chosen for the VP and KP procedures. Cement augmentation was performed according to common instructions already brought in the literature. The VP and KP procedures were performed by needle insertion through the pedicle. The PMMA was used as the bone cement. The volume fraction for the consumed PMMA was 20% of the whole vertebral volume. The cement distribution was checked by CT scanning of the samples after cement augmentation.

Micro finite element modeling

To reconstruct three dimensional micro structure of trabecular bone, a micro computed tomography (μCT 100, SCANCO Medical AG, Switzerland) was used for a specimen treated by VP and KP. To evaluate the regional variations of stress distribution inside the vertebrae, each specimen was subdivided to 9 smaller cubes with the size of 5 mm × 5 mm × 5 mm in 3 layers (Figure 1). Then the model was imported into the analytical software ABAQUS 6.14.

Implant design

The hexagonal porous structure was set on one cube instead of the bone cement mass. For designing the implant, two geometrical parameters were considered as: Spacing diameter and thickness (Figure 2). The implant design was performed in four groups with different geometries. The geometrical characteristics of the hexagonal structure including thickness and spacing diameter, are presented in Table 1. There was also a pattern among the designed implants: The thickness of

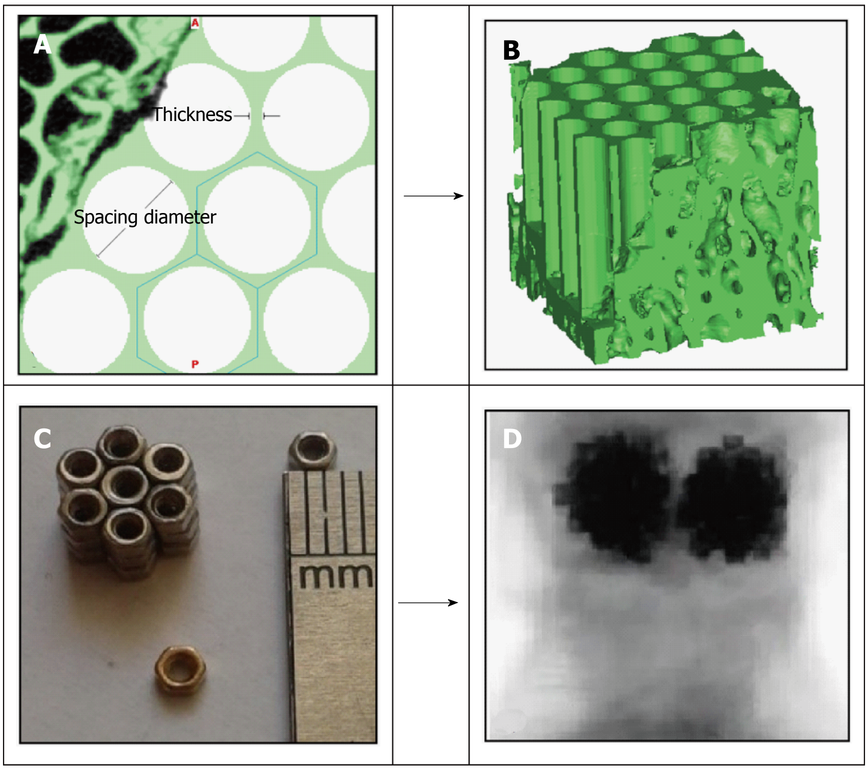

Figure 2 Spacing diameter and thickness. A and B: Design of hexagonal porous structure; C and D: Using a symmetric circle pattern equivalent to; the embedded hexagonal structure in the experimental study (Ref [21]), already performed.

Table 1 Geometrical parameters in implant design

	Model 1	Model 2	Model 3	Model 4
Thickness (mm)	0.5	0.4	0.3	0.2
Spacing diameters (mm)	1	1.5	2	2.3

Table 2 Material properties used in the finite element method

Components	Elastic modulus (MPa)	Poisson ratio
Trabecular bone	30	0.2
Bone cement	2530	0.2
Steel	200e3	0.3
Titanium	110e3	0.3

the structure was decreased simultaneously with growing the spacing diameter from the models 1 to 4. The hexagonal porous implants were designed in the way to replace the cement mass on one cube in four models with two groups of materials: Steel and titanium. The porous structure is set in the space already occupied by the cement mass. The symmetric circle pattern was used to construct the hexagonal structure equivalent to the experimental study[21], previously performed. Material properties including elastic modulus and Poisson ratio used in the FEM are shown in Table 2.

Loading

In accordance with micro finite element analyses (μFEA) performed by Gong *et al*[22], to simulate the experimental testing conditions, a displacement load was applied as 1% compressive strain on the longitudinal direction with the full constraints at the bottom of each trabecular cube.

RESULTS

The results of μFEA of cubes related to VP and KP indicated that the maximum Von misses stress in the cubes of the VP was less than that of the KP. Basically, the mechanical behavior of a construction made of the bone cement and trabecular structure is based on the cement distribution. As shown in Figure 3, the cement distribution in trabecular cubes is totally different in the VP and KP.

The results of μFEA of the cubes surrounding the injected cement mass in both VP and KP indicated the low regional variations in the amount of maximum Von Misses stress in the cubes 1 to 6 with the average value of 21.7 MPa and 36.6 MPa for the VP and KP, respectively. Also, in the third layer without cement penetration, for cubes 7 to 9, the difference between the amounts of maximum Von Misses stress in the cubes was not considerable and had the average value of 7.3 and 7.21 MPa for the VP and KP.

The low regional variation in the cubes with combination of bone cement and trabecular bone in the KP, made the selection of each cube for embedding the hexagonal structure, a reasonable statistical one. Therefore, the results of analyses for the selected cube were generalizable to the whole vertebra. The

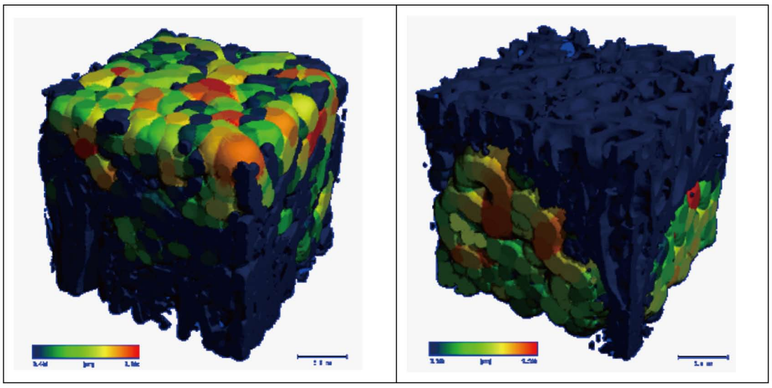

Figure 3 Different cement distribution in the vertebroplasty (left) and kyphoplasty (right).

maximum Von misses stress in the cube 2, with the embedded hexagonal porous structure with different geometries, instead of the cement mass, is shown in Figure 4. The maximum Von Misses stress in the cube with hexagonal structure was more than that of the same cube treated by KP procedures at first. But after implementing different geometrical parameters of the hexagonal structure, the maximum Von Misses stress was decreased in the whole cube. This was the sign of altered stress distribution inside vertebrae.

For the model 1, with the thickness of 0.5 mm and spacing diameter of 1 mm, the maximum Von-Misses stress for the implant material of steel and titanium was 38.2 and 37.8 MPa, respectively. For the model 2, with 0.4 and 1.5 mm for the thickness and spacing diameter, the maximum Von-Misses stress reduced to 34 and 32.2 MPa for steel and titanium implants, respectively. This decreasing trend in the amount of Von Misses stress was continued until reaching to 16.5 and 16.4 MPa for the steel and titanium implants in the model 3, with the 0.3 and 2 mm for the thickness and spacing diameters. But after this, increasing the spacing diameter and decreasing the thickness in the hexagonal structure, caused the enhancement of Von Misses stress in model 4.

The diagrams of vertebrae with hexagonal structure, indicated two main points: (1) after implementing geometrical parameters of the hexagonal structure, the amount of maximum Von Misses stress in the construction was decreased; and (2) the influence of type of material (steel or titanium) on the amount of maximum Von Misses stress was less obvious than the impact of implant geometry.

DISCUSSION

This study was set to compare the mechanical behavior of the vertebrae treated by the VP and KP with the one treated by the hexagonal porous structure having different geometries. In the case of VP, the bone cement filled most of the porous space of the trabecular structure, such that the whole construction was almost homogeneous. This was the reason for increasing the stress in endplates, pressure inside disks and the bulge of adjacent endplates leading to occurring adjacent fractures[4]. On the other hand, in the KP, the bone cement mass and the trabecular structure were separated and the whole structure was not homogeneous. So the stress concentration could be seen in the interface area. The stress concentration in the separation region caused high amounts of Von Misses stress in the construction.

The results of an experimental study addressing the differences between the mechanical behavior of the vertebrae treated by hexagonal pearls embedded inside vertebrae and that of the VP and KP[21], confirmed the results of μFEA in this study. Based on the results of mechanical tests, by setting the hexagonal porous structure, the toughness of the vertebra was enhanced substantially in the form of increased range of displacement of the vertebrae (83%) before getting to the ultimate strength under static loading. Also, the effect of the type of material in increasing the toughness was less obvious when compared to the effect of implant shape. In the KP, the separation area between the rigid cement mass and the trabecular bone was the most susceptible region for occurring fractures because the stress distribution in the boundary region was not homogeneous. The hexagonal porous structure rendered better stress distribution in the boundary region and reduced the risk of fracture in the future.

The complicated geometry of trabecular bone requires an algorithm to determine the amount and the position of bone cement or any other structure. The improvement in stress distribution inside treated vertebrae leads to the reduction of stress in endplates[6]. So it could be inferred that the treated vertebrae by the hexagonal structure is likely to encounter a less amount of stress in endplates. As the treated vertebrae by hexagonal structure had better stress distribution, it could be predicted that in the term of long term stability, those vertebrae might show a better performance.

The decreasing trend in the maximum Von Misses stress in the cube with the hexagonal porous structure can be obviously seen in Figure 4. The improvement in the mechanical behavior of the whole vertebra treated by new method, as compared to the common procedures, could be achieved by validating the

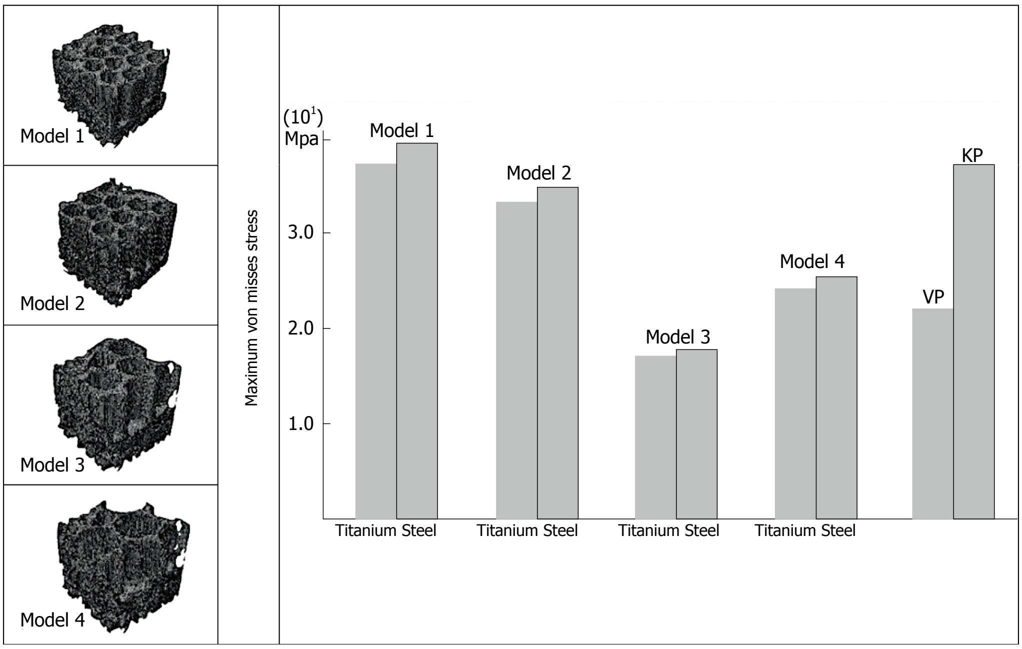

Figure 4 Maximum von misses stress in the cube with geometrically different hexagonal structures: model 1 to 4 and also in the vertebroplasty and kyphoplasty in the form of bar graph.

theoretical results through experimental tests. The reduction of Von Misses stress in the construction after implementing geometrical parameters is comparable to the results of the experimental tests already performed, thereby showing the increased range of displacement before getting to the ultimate strength in the vertebrae treated by the hexagonal structure; this represented the better stress distribution inside the vertebrae under the uniaxial compressive load. The increasing trend in Von Misses stress in the model 4 indicated the existence of an optimal amount for the geometrical parameters of hexagonal structure. Considering the morphological parameters of trabecular cube such as Tb. Th and Tb. Sp, it seems that there is a relationship between geometrical parameters of the embedded structure and morphological parameters of trabecular bone. Therefore, optimizing the design of implants is related to those morphological parameters.

The more dependence of stress distribution on different geometries of implant, compared to the variation of material in the results of μFEA, was also observed in the experimental study[21], this showed that the influence of the material of hexagonal structure in increasing the range of displacements before getting to the ultimate strength (improved stress distribution), as compared to the impact of implant geometry, is of secondary importance.

Future studies must be focused on optimizing the geometry of the hexagonal implants based on morphological parameters of trabecular structure in order to provide clear surgical instructions for each patient. In addition to the improvement of mechanical properties of the treated vertebrae, setting porous scaffolds might help better bone regeneration, cell migration and bone repair.

In conclusion, the new method presented here is based on using hexagonal implants instead of the rigid cement mass. The results of treated vertebrae by hexagonal structures showed that the improvement of the stress distribution inside vertebrae could lead to increasing the toughness and reducing stress in endplates. Also, because the hexagonal porous structure was symmetrical and geometrically optimized, it could solve the problem of asymmetrical cement distribution, a common problem in the VP and KP. The results of this study indicated that a wide range of material could be selected in providing implants due to the low dependence of stress distribution, relative to the implant material variance.

Future studies must be focused on evaluating geometrically different models of implants based on defined parameters of this study: Thickness and spacing diameter; this could lead to optimizing the stress distribution considering the morphological parameters of trabecular bone for each patient. Also, advanced techniques to facilitate the insertion of porous structures inside vertebrae must be considered. In the case of long term stability, *in-vivo* studies could be an effective method to assess the bone repair and evaluating the durability.

COMMENTS

Background

The vertebroplasty (VP) and kyphoplasty (KP) are known as common procedures in treating osteoporotic vertebrae. Although post treatments of KP are less than those of VP, but the stress concentration in the interface area of bone cement and trabecular bone could be regarded as the main reason of occurring micro fractures, pain and aseptic loosening.

Research frontiers

Previous researches have already proved that cement augmentation increases the interadiscal pressure in adjacent discs with a slight increase in Von Mises stress in vertebral endplates. Basically, the main drawbacks of cement augmentation are: (1) stress concentration in the interface area; and (2) asymmetrical cement distribution.

Innovations and breakthroughs

This is the first study addressing the hexagonal porous structure with defined geometrical parameters including spacing diameter and thickness. It was conducted to alter the mechanical behavior of the osteoporotic vertebrae.

Applications

The hexagonal porous structures could be considered as a substitute for bone cement with the variety of geometrical parameters. Furthermore, setting porous structures with different geometries inside vertebrae may provide the possibility of bone regeneration, transfer of the growth factors and recreation of mechanical properties.

Terminology

The hexagonal porous structure could be considered as a substitute for bone cement mass due to lowering the level of the maximum Von Mises stress and reducing the stress concentration and post treatments. Within defined geometrical parameters, thickness and spacing diameter, the structure could be optimized as well.

Peer-review

Good study, subject addressed in this article is worthy of investigation.

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P- Reviewer: Chowdhury FH, Elgafy H **S- Editor**: Cui LJ
L- Editor: A **E- Editor**: Lu YJ

World Journal of Orthopedics

Submit a Manuscript: http://www.f6publishing.com

World J Orthop 2017 November 18; 8(11): 836-845

DOI: 10.5312/wjo.v8.i11.836

ISSN 2218-5836 (online)

ORIGINAL ARTICLE

Retrospective Study

Atlantoaxial rotatory displacement in children

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Author contributions: Spiegel D and Dormans J came up with the study questions; Spiegel D, Shrestha S, Sitoula P and Rendon N contributed to the study design and IRB application; Spiegel D, Shrestha S, Sitoula P and Rendon N reviewed all of the studies and collected the data; Spiegel D was the primary author of the manuscript; Shrestha S and Sitoula P were secondary authors; Rendon N and Dormans J reviewed the manuscript and provided critical revisions; all authors provided final approval for the article.

Institutional review board statement: The study was reviewed and approved by the Children's Hospital of Philadelphia's Institutional Review Board.

Informed consent statement: A waiver of informed consent has been granted by the Children's Hospital of Philadelphia's Institutional Review Board to conduct this retrospective study.

Conflict-of-interest statement: The authors declare that they have no conflicts of interest related to this work. Dr. Spiegel has received royalties from Springer for co-editing a textbook.

Data sharing statement: The data is available at request from the corresponding author.

Manuscript source: Unsolicited manuscript

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Received: January 4, 2017
Peer-review started: January 6, 2017
First decision: February 17, 2017
Revised: March 20, 2017
Accepted: April 6, 2017
Article in press: April 10, 2017
Published online: November 18, 2017

Abstract

AIM

To correlate the Pang and Lee class with the clinical course in a consecutive series of patients presenting with painful torticollis.

METHODS

Forty-seven dynamic rotational computed tomography (CT) scans in 35 patients were classified into one of the five types defined by Pang and Li, including types Ⅰ (atlantoaxial rotatopry fixation), Ⅱ ("pathologic stickiness" without crossover of C1 on C2), Ⅲ ("pathologic stickiness" with crossover of C1 on C2), Ⅳ (normal or muscular torticollis), and Ⅴ (diagnostic grey zone). The Pang and Li class was then compared with the radiologist's report, which was graded abnormal, diagnosis of rotatory subluxation or fixation, or non-diagnostic. Medical records were reviewed and the clinical course was compared among the five subtypes.

RESULTS
We reviewed 47 CT scans in 35 patients, and the majority were performed without sedation. The average age was 7.7 years (4-14 years old) and associated conditions included minor trauma (20%), surgical procedures around the head and neck (29%), and Grisels syndrome (20%). Twenty-six percent of our studies fell within the pathologic spectrum (5% type 1 or rotatory fixation, 21% types 2 and 3 or rotatory subluxation), while 45% were classified as muscular torticollis (45%) and 28% fell within the diagnostic grey zone. Seven radiologists interpreted these studies, and their interpretation was discordant in 45% of cases. Clinical resolution occurred in 27 of 29 cases for which follow-up was available. One of two patients with fixed rotatory subluxation required a C1-C2 arthrodesis.

CONCLUSION
The Pang and Li classification characterizes a spectrum of abnormalities in rotation to facilitate communication, although the indications for dynamic CT scan should be further defined.

Key words: Atlanto-axial rotatory subluxation; Atlanto-axial rotatory fixation; Dynamic rotational computed tomography; Atlanto-axial rotatory displacement

Core tip: Atlantoaxial rotatory displacement represents a spectrum of pathology. We classified 47 computed tomography (CT) scans in 35 patients presenting with painful torticollis according to Pang and Li, and found that the radiologist's interpretation was discordant in 45%, suggesting the need to develop a common language with our imaging colleagues to accurately describe this pathology in the individual patient. Most patients resolved with non-operative treatment, although one of two with fixed rotatory subluxation required a fusion. As 74% were classified as muscular torticollis (45%) or fell within the diagnostic grey zone (28%), the indications for a dynamic CT scan should be revisited.

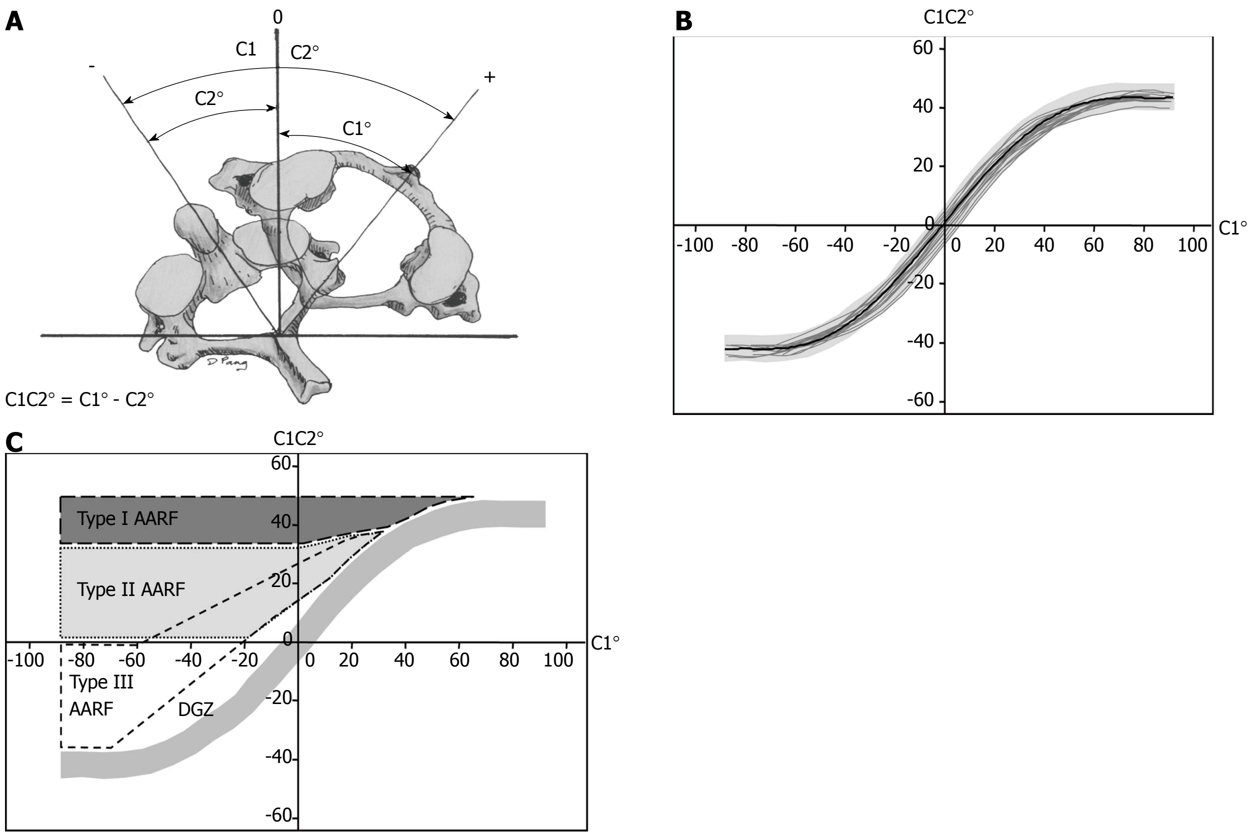
Spiegel D, Shrestha S, Sitoula P, Rendon N, Dormans J. Atlantoaxial rotatory displacement in children. *World J Orthop* 2017; 8(11): 836-845 Available from: URL: http://www.wjgnet.com/2218-5836/full/v8/i11/836.htm DOI: http://dx.doi.org/10.5312/wjo.v8.i11.836

INTRODUCTION

A variety of terms have been used to describe a spectrum of rotational abnormalities of the atlantoaxial joint observed in the absence of major trauma, most commonly atlantoaxial rotatory displacement, atlanto-axial rotatory subluxation (AARS) and atlanto-axial rotatory fixation (AARF)[1-12]. This lack of uniformity in terminology reflects the challenges of capturing dynamic rotational abnormalities occurring within the physiologic range of motion. As a loss of contact between the facets at C1 and C2 of up to 85% occurs during the extremes of physiologic rotation, subluxation is a normal finding and "pathologic" cannot be defined by the relationships between C1 and C2 at any particular point within the arc of rotation[13,14]. The dynamic computed tomography (CT) scan has been utilized to evaluate children presenting with a painful torticollis, although diagnostic imaging criteria have not been established. Pang and Li have developed a diagnostic approach in which measurements extracted from the dynamic rotational CT scan are plotted on a graph and compared with normative data[5-7]. The goal of this retrospective radiographic and clinical review is to correlate the Pang and Li class with the clinical course in a consecutive series of patients presenting with painful torticollis.

MATERIALS AND METHODS

Pang and Li first defined normal composite rotational motion curves from dynamic rotational CT scans in 21 pediatric patients who had no signs or symptoms of atlanto-axial rotatory dysfunction (3 to 11.5 years of age)[5]. For each position of cervical rotation, they first measure the angle between the vertical axis and the sagittal axis of the occiput, C1, and C2. They then plot the C1 angle (head position) on the X axis and the C1-C2 angle (angle of separation or divergence) on the Y axis (Figure 1A and B). They identified three distinct phases within the normal motion curve (Figure 1B). C1 rotates in isolation during the first or "single motion" phase (0°-23°), and from 24°-63° both C1 and C2 rotate at different rates increasing the angle of separation or divergence to a maximum of approximately 45°. Rotation beyond 63° occurs through the subaxial spine with no further divergence between C1 and C2. C1 normally crosses over C2 at the zero or null point. This normative data provides a template of how C1 and C2 relate throughout the range of head positions, and was compared with data from patients presenting with painful torticollis to develop a classification system (Figure 1C)[6,7]. In patients with type Ⅰ dynamics, C1 and C2 are locked (< 20% correction in separation angle through range of motion). This type might be referred to as AARF. In type Ⅱ and type Ⅲ there is a "pathologic stickiness" between C1 and C2; while mobility between C1 and C2 is preserved (> 20% correction in separation angle), C1 either does not (type Ⅱ) or does (type Ⅲ) cross over C2. Normal dynamics are observed in type 4 (muscular torticollis). In the type 5 or diagnostic grey zone, C1 crosses over C2 at a point between 8 and 20 degrees beyond the midline;



Figures 1 Classification by Pang and Li. A: Measurements from the dynamic CT scan include the angles between C1 and C2 relative to the vertical axis, and the C1C2 angle is then calculated. By convention, positive values are assigned to the presenting side (side to which the chin points at presentation of torticollis) and negative is assigned to the opposite side (corrected side). Normative data is depicted as motion curves in which the C1 angle is plotted against the C1C2 angle (1B), and the different classes are illustrated as shaded areas in (C) (Figure 1A reprinted with permission from Pang D, Li V, Atlanto-axial rotatory fixation: part 2--new diagnostic paradigm and a new classification based on motion analysis using computed tomographic imaging. Neurosurgery 2005; 57: 941-953. Figures 1B and C reprinted with permission from Pang D, Li V. Atlantoaxial rotatory fixation: Part 1-Biomechanics of normal rotation at the atlantoaxial joint in children. Neurosurgery 2004; 55: 614-625).

the authors feel that this may represent a transitional type of dynamics which may either revert to normal or progress to one of the more severe forms of the condition. For clinical applications, the authors obtain the CT scan with the patients head in a comfortable position (P or presenting position, side to which the chin is rotated), with the nose pointing straight upwards (P_0 or neutral position, partially corrected), and with the head rotated maximally to the opposite side (P_-, maximally corrected position). By convention all values towards the presenting side are positive, and towards the opposite or corrected side are negative (Figure 1A).

We searched the database from our radiology department to identify all patients who underwent a dynamic rotational CT scan over seven consecutive years since a digital imaging system became available. Approval from the Institutional Review Board was obtained. The imaging protocol involved 1.5 millimeter cuts between the occiput and C3 with the patient' s shoulders flat and the head positioned at neutral, and with maximal voluntary rotation to the right and to the left. Digital calipers were used to measure the angle between the vertical axis and the sagittal axis of each bone (occiput, C1, and C2) at all three positions of cervical rotation (right, left, neutral). The angle of divergence between C1 and C2 (C1-C2 angle) was also calculated for each position of rotation. Three observers evaluated each CT scan independently (PS, SS, DS), and the reviewed each study together and constructed the graphs which were compared with the normative template provided by Pang and Li (types Ⅰ-Ⅲ = abnormal or within spectrum of AARS), type 4 = normal, type 5 = Diagnostic Grey Zone) (Figure 1B and 2). We reviewed the radiologist's interpretation, which we graded as (1) positive (diagnosed as AARS or AARF); (2) negative; or (3) non-diagnostic.

We then reviewed each patient's medical records with regard to age, gender, potential associations (minor trauma, inflammatory conditions, recent surgery around the head or neck), delay from symptom onset to presentation, treatment prior to referral, treatment course including immobilization, and outcomes (resolved, persisted, recurrent). We correlated the patient's overall treatment course and outcomes for each of the 5 types. Patients who were imaged more than once were grouped according to their most severe type.

RESULTS

We reviewed 47 CT scans in 35 patients, and only

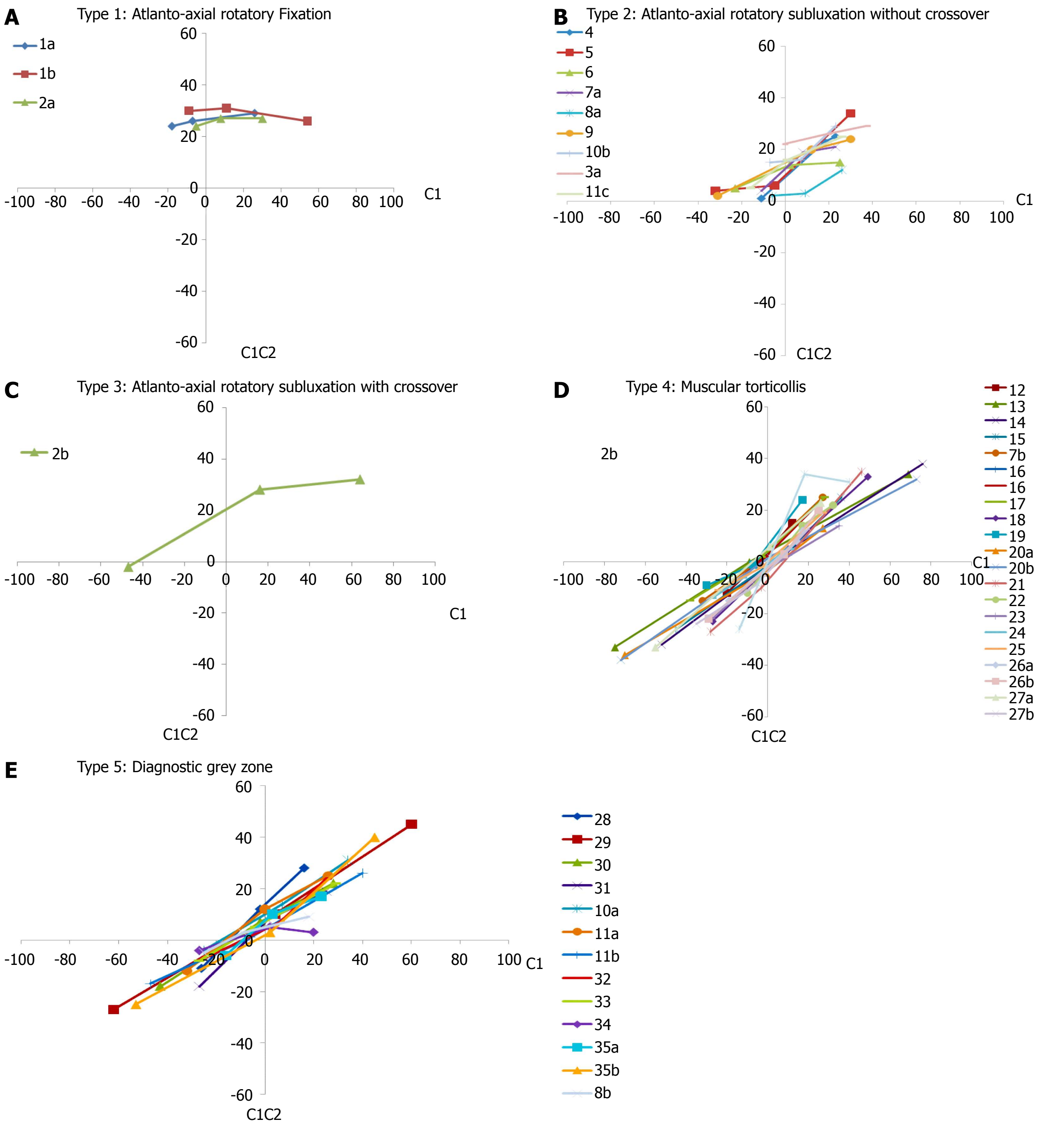


Figure 2 Atlanto-axial rotatory subluxation and fixation. A: Type 1 (fixation). Three studies (two patients) could be classified as a fixed rotatory subluxation, in which there was less than 20% correction of the C1C2 angle on maximal rotation to the opposite side; B: Type 2 (pathologic stickiness without crossover). Eight studies illustrated an improvement in the angle of divergence of more than 20%, but C1 did not cross over C2; C: Type 3 (pathologic stickiness with crossover). In three studies there was improvement in the C1C2 angle and C1 did cross over C1, but well beyond the null point or midline; D: Type 4 (normal dynamics, muscular torticollis). Twenty-one of our studies exhibited normal dynamic curves and could be classified as muscular torticollis; E: Type 5 (diagnostic grey zone). Ten studies fell into the diagnostic grey zone. In these cases the C1 crossover was delayed and occurred at 8°-20° beyond the midline or null point.

26% (12/47) of our studies fell within the pathologic spectrum from rotatory subluxation (21% types 2 and 3) to rotatory fixation (5% type Ⅰ) (Table 1). Forty-five percent fell within the physiologic range (muscular torticollis), and 28% were in the diagnostic grey zone. Ten of our patients were imaged more than once. Normal dynamics was observed in two separate studies in 3 patients. One follow-up study demonstrated restoration of normal dynamics, and improvement was observed in 3 cases (type 1-3, type 2-4, type 2-5). There was either no change or progression to a higher class in 3 cases. A single patient had 3 studies performed, and while the first two were classified in the diagnostic grey zone, the third demonstrated type Ⅱ dynamics. Two of these studies were performed with sedation, and a third in the operating room under

Table 1 Radiographic findings (*n* = 47)

Pt. #	Rotation	Presenting position (P) (maximum rotation towards presenting side)				Neutral (Po) (partially corrected position)				Corrected position (P-) (best corrected position)				% Correction	Pang class	Rad int	Radiologist
		Oc	C1	C2	C1C2	Oc	C1	C2	C1C2	Oc	C1	C2	C1C2				
1a	R	30	26	-3	29	-1	-7	-31	26	-22	-18	-42	24	17%	1	Yes	4
1b	L	45	54	31	26	13	11	-20	31	-23	-9	-39	30	15%	1	Yes	1
2a	L	17	30	-3	27	-3	8	-21	27	-15	-5	-29	24	11%	1	ND	1
3a	L	38	37	8	29	20	19	-7	26	-2	-1	-23	22	24%	2	Yes	3
4	L	24	23	-2	25	16	18	-5	23	-10	-11	-12	1	96%	2	Yes	2
5	L	29	30	-4	34	4	-5	-11	6	-30	-32	-36	4	88%	2	ND	7
6	L	23	25	10	15	2	2	-12	14	-20	-23	-28	5	66%	2	No	1
7a	R	18	23	2	21	-2	8	-11	19	-19	-11	-15	4	81%	2	Yes	2
8a	R	25	26	14	12	7	9	6	3	-3	-6	-8	2	83%	2	ND	7
9	L	24	30	6	24	4	12	-8	20	-34	-31	-33	2	92%	2	No	3
10b	R	16	23	-6	29	-4	7	-9	16	-22	-7	-22	15	91%	2	Yes	2
11c	L	21	26	1	25	-7	1	-15	16	-25	-16	-21	5	NA	2	Yes	5
2b	L	53	64	32	32	-2	16	-12	28	-61	-47	-45	-2	NA	3	Yes	1
12	L	10	12	-3	15	-2	-4	-4	0	-13	-20	-8	-12	NA	4	No	1
13	L	67	69	35	34	-6	-9	-9	0	-80	-75	-42	-33	NA	4	No	2
14	R	73	76	38	38	2	11	6	5	-58	-52	-20	-32	NA	4	No	1
15	R	34	36	11	25	8	10	6	4	-48	-45	-19	-26	NA	4	No	7
7b	R	27	27	2	25	-10	-10	-7	-3	-30	-32	-17	-15	NA	4	Yes	1
16	R	22	23	2	21	-1	-1	-3	2	-20	-18	-9	-9	NA	4	ND	7
17	R	33	28	3	25	-1	-3	-5	2	-38	-38	-23	-15	NA	4	ND	4
18	R	44	49	16	33	5	10	5	5	-33	-27	-4	-23	NA	4	No	5
19	R	18	17	-7	24	-7	-7	-6	-1	-28	-30	-21	-9	NA	4	No	1
20a	L	24	27	14	13	-6	-1	3	-4	-71	-70	-34	-36	NA	4	ND	3
20b	L	76	73	41	32	-5	1	3	2	-71	-72	-34	-38	NA	4	No	1
21	R	47	46	11	35	-2	-3	7	-10	-29	-28	-1	-27	NA	4	No	2
22	L	20	32	10	22	8	17	6	14	-20	-10	2	-12	NA	4	ND	3
23	L	32	35	21	14	-1	-1	2	-3	-28	-27	-5	-22	NA	4	No	2
24	L	9	11	6	5	9	-12	-6	-6	-22	-27	-13	-14	NA	4	No	7
25	L	27	27	24	19	5	-3	-1	-2	-20	-24	-13	-11	NA	4	No	1
26a	L	15	17	5	12	15	14	6	8	-21	-19	-4	-15	NA	4	ND	7
26b	L	23	25	5	20	7	8	5	3	-29	-29	-7	-22	NA	4	ND	3
27a	L	27	26	3	23	1	1	-5	6	-64	-55	-22	-33	NA	4	ND	1
27b	L	24	20	7	13	-3	-6	3	-9	-30	-35	-11	-24	NA	4	No	3
3b	R	37	40	9	31	16	18	-16	34	-12	-14	12	-26	NA	4	Yes	3
8b	L	18	18	12	9	-6	-9	-12	3	-21	-25	-20	-5	NA	5	ND	5
28	R	18	16	-12	28	1	-2	-14	12	-23	-26	-15	-11	NA	5	No	1
29	L	66	60	16	45	1	4	-6	10	-69	-62	-35	-27	NA	5	No	2
30	R	31	28	6	22	-3	-2	-9	7	-42	-43	-25	-18	NA	5	No	1
31	L	23	25	6	19	3	1	-7	8	-20	-27	-9	-18	NA	5	Yes	2
10a	R	30	34	3	31	-2	7	-7	14	-29	-25	-21	-4	NA	5	Yes	2
11a	L	21	26	1	25	7	0	-12	12	-34	-32	-20	-12	NA	5	Yes	1
11b	L	33	40	14	26	-6	-6	-7	1	-62	-47	-30	-17	NA	5	Yes	6
32	R	25	25	1	24	2	6	-13	7	-25	-27	-19	-8	NA	5	No	3
33	R	29	29	7	22	-2	-4	-9	5	-27	-27	-19	-8	NA	5	No	7
34	L	22	20	23	3	3	2	-3	5	-29	-27	-23	-4	NA	5	No	7
35a	L	21	23	6	17	4	3	-7	10	-18	-16	-12	-6	NA	5	Yes	2
35b	L	41	45	5	40	-1	2	-1	3	-50	-53	-18	-25	NA	5	Yes	1

A variety of data was collected from the imaging studies including patient number, presenting side, measurement angles (occipital, C1, C2, C1C2) for the presenting position, neutral position, and corrected positions, as well as the percentage of correction in divergence angle for types II and III, the type according to Pang and Li, the radiologist's interpretation (Yes, No, Non-diagnostic) and the radiologist who evaluated each study (1-7). For the radiologists interpretation; Yes: AARF; No: Normal or muscular torticollis; ND: No clear diagnosis established; NA: Not applicable.

general anesthesia.

Seven radiologists interpreted these studies. For studies classified as types 1 through 3, the radiologist's interpretation was concordant in 8/13 (62%) (Table 1). Two of the other 5 studies were read as normal and three were non-diagnostic. In the 21 studies graded as type 4 (normal or muscular torticollis), 12 (57%) were read as normal and of the remaining 9 (43%) were read as AARF (2) or non-diagnostic (7). For those studies in the diagnostic grey zone (type 5), the radiologists interpreted 46% (6/13) as normal, 46% (6/13) as AARF, and 8% (1/13) as non-diagnostic.

Our study population included 19 females and 16 males, and the average age was 7.7 years (range 4-14 years). All patients had neck pain, torticollis, and a normal neurologic examination. Associated conditions

Table 2 Associated conditions

Associations	Pang class and associations	
Minor trauma (7)	I	Minor trauma (2)
ENT or craniofacial procedures (10)	II	Craniofacial procedures (3)
		ENT procedures (3)
		Grisels (1)
		Unknown (2)
Grisels (7)	III	Minor trauma (1)
Unknown (8)	IV	Unknown (6)
		ENT procedures (3)
		Grisels (3)
		Minor trauma (3)
		Occipital condyle fracture (1)
Occipital condyle fracture (1)	V	Grisels (3)
		ENT procedures (2)
Down syndrome (1)		Minor trauma (2)
		Unknown (1)
Congenital muscular torticollis (1)		Down syndrome (1)

The conditions associated with the painful torticollis are illustrated on the left side, and on the right side these associations are grouped according to the Pang and Li type.

are listed in Table 2, and included minor trauma (20%), craniofacial or ENT procedures (29%), and Grisel syndrome (20%). Sufficient clinical information could be retrieved for 29 of 35 patients (Table 3). The time from the onset of symptoms to presentation ranged from three days to five months, and seven of the patients were treated by a variety of methods prior to referral to our orthopaedic service. Three patients were evaluated in our emergency room and were never seen by orthopaedics, while two others were seen once as outpatients for a second opinion. Patients having more than one study are grouped according to their highest grade of involvement.

Two patients were classified as having type 1 dynamics, or a true fixed rotatory subluxation. The first presented after 6 mo of previous treatment with skin traction, skeletal traction and bracing. Reduction was achieved with skeletal traction, but could not be maintained, and a C1-C2 arthrodesis was required. The second patient presented one month after the onset of symptoms and failed two courses of skin traction and bracing, during which her dynamics had improved from type Ⅰ to type Ⅲ. She was then treated by skeletal traction, and ultimately reduced and was managed in a pinless halo for 3 mo. She remains asymptomatic at more than 3 years follow-up.

Nine patients had type Ⅱ (8) or type Ⅲ (1) dynamics, five of whom were scanned more than once. Six were admitted for soft cervical traction (4-14 d) and then immobilized in a soft collar, hard collar, or pinless halo for an additional 2-8 wk. Two were managed with a soft collar and oral medications. While follow-up was limited, resolution was observed in eight patients. A single patient had persistent and intermittent symptoms, and initially had two studies that were in the diagnostic grey zone, and the third had demonstrated progression to a type Ⅱ rotatory subluxation.

Sixteen patients exhibited normal dynamics (type 4, muscular torticollis). Four were never evaluated by orthopaedics, and two were seen once for an outpatient consultation. All but one of the remaining patients had clinically resolved at one to twenty weeks follow-up. Four patients were admitted for soft cervical traction, and seven were managed by nonsteroidal anti-inflammatory medications with or without a soft or hard cervical collar, or by physical therapy. A single patient with a history of congenital muscular torticollis and an acute episode of pain was treated by a bipolar sternocleidomastoid release once symptoms had abated.

Eight patients fell within the diagnostic grey zone (type 5). Five patients were effectively treated by soft cervical traction (2-10 d), with no relapse at two to twenty weeks follow-up. Of three patients treated by a soft collar and analgesics, one had resolved at 8 wk follow-up and records could not be obtained for the other two. Due to behavioral issues, a single patient with Down syndrome could not be imaged at presentation, and could not be maintained in halter traction despite oral sedation and analgesics. The decision was made to perform a dynamic rotational CT scan under anesthesia using the O-arm, and the diagnosis was muscular torticollis. The torticollis resolved with immobilization and physical therapy, and has not recurred at more than 2 years follow-up.

DISCUSSION

The terms atlanto-axial rotatory displacement (AARD), subluxation (AARS), and fixation (AARF) have all been used to describe a spectrum of rotational abnormalities of the atlanto-axial joint observed in the absence of major trauma[1-12]. Associated conditions include minor trauma[1,15], inflammatory disorders (Grisel syndrome)[3,16,17], or surgical procedures on the head or neck[6,7,17-20]. Predisposing factors may include anatomic features (horizontal facet orientation, facets shaped like biconvex discs, joint hypermobility), mechanical loading (intraoperative positioning, loss of normal muscle tone during general anesthesia), and physiologic factors (hyperemia from infection or inflammation) associated with increased mobility. Anatomic barriers to achieving reduction include inflamed synovial and/or capsular tissues[1,2,10] or abnormalities of a meniscus like synovial fold at the periphery of the joint (inflammation, rupture, in-folding)[21]. Pathologic findings identified in chronic cases include contracture of periarticular soft tissues, interposition of fibrous tissue, osseous cross union, and adaptive changes in facet morphology[1,7,15,22-24]. A timely diagnosis is critical, and the results following treatment are less predictable when the condition presents at a subacute (> 1 mo) or chronic stage[1,7], recurs, or presents with a fixed subluxation between C1 and C2[7].

Normal cervical rotation is approximately 70°-80° to each side in both children and adults[13,14], and the maximum divergence between C1 and C2 during

Table 3 Clinical findings

Pt #	Pang	Age	Gen	History	Delay to initial presentation	Prior treatment	1° Rx.	Dur (d)	Results	2° Rx.	Dur (d)	Results	3° Rx.	Dur (wk)	Outcome	Immobilization	FU (wk)	Final results
1	1, 1	8	F	Fell backwards while walking	3 wk initial, referred after 6 mo	3, 5	5	14	3	6		1				PH × 6 wk, SC × 1 wk	108	1
2	1, 3	8	F	Shaking water from ear	4 wk	3, PT	4	7	3	4	10	3	5	3	1	PH × 3 mo	150	1
3	2, 4	7	M	Goldenhar syndrome, ear reconstruction	7 d	None	4	8	1	-	-	-	-	-	-	PH × 4 wk	NR	1
4	2	6	F	Crouzon syndrome, midfacial advancement	None	None	4	10	1	-	-	-	-	-	-	PH × 4 wk	2	1
5	2	10	F	Pharyngitis	7 d	None	4	14	1	-	-	-	-	-	-	PH × 2 mo	6	1
6	2	7	M	Awakened with stiff neck	10 d	None	4	3	2	4	4	2	-	-	-	None	2	1
7	2, 4	13	F	ADN	7 d	None	4	7	1	-	-	-	-	-	-	HC × 6 wk	2	1
8	2, 5	7	M	Tonsillectomy/ADN, Klippel-Feil	5 d	None	4	7	1	-	-	-	-	-	-	SC	2	1
9	2	8	F	Tonsillectomy/ADN	4 d	None	1	10	2		NR	2	NR	NR	NR	SC	1.5	1
10	5, 2	5	M	Golderhar Syndrome, Hemifacial microsomia. 2 episodes S/P mandibular reconstruction and zygoma and mandible reconstruction	4 d	None	4, 4	4, 5	1	-	-	-	-	-	-	PH × 4 wk, HC × 3 wk		1
11	5, 5, 2	9	M	Neck pain	Unknown	None	4	5	3	-	-	-	-	-	-	PH × 3 wk	18	3
12	4	6	M	Unknown	Unknown	None	1	-	-	-	-	-	-	-	-	-	-	No Ortho
13	4	5	M	Unknown	4-5 mo	None	Outpatient consult	-	-	-	-	-	-	-	-	None	NA	1
14	4	6	F	Scarlet fever	6 wk	6 wk of oral antibiotics	Outpatient consult	-	-	-	-	-	-	-	-	-	NA	1
15	4	6	M	Unknown	ER	None	1	-	-	-	-	-	-	-	-	-	-	No Ortho
16	4	8	M	Unknown	ER	None	3	-	-	-	-	-	-	-	-	PH × 8 wk	-	No Ortho
17	4	9	M	All terrain vehicle injury, occipital condyle fracture	None	None		1	-	-	-	-	-	-	-	-	20	1
18	4	6	F	Cervical lymphadenitis	None	2	4	-	-	-	-	-	-	-	-	HC × 1 wk	1	1
19	4	5	F	Congenital muscular torticolis	1 mo	Torticolis sx at 1.5 yr of age	Bipolar Release	-	1	-	-	-	-	-	-	-	-	-
20	4, 4	12	F	Retropharyngeal abscess	3-4 d	None	4	10	1	-	-	-	-	-	-	SC × 2 wk	3	1
21	4	6	M	Throwing ball	2 wk	4	4	14	2	-	7	2			2	Persistent	1	1
22	4	9	F	Unknown	None	None	PT	-03/17/003	-		-	-	PT			Recurrence	18	-
23	4	7	F	Choanal Atresia repair, ADN	2 d	2	1	2	2	4	-	-	-	-	-	CTO × 6 wk	9	1
24	4	8		Wrestling	None	None	3		-	-	-	-	-	-	-	HC	-	No FU
25	4	10	M	ADN	None	None	3	.	-	-	-	-	-	-	-	-	-	
26	4, 4	8	F	Minor trauma doing handstand	None	None	4	5	1	-	-	-	-	-	-	-	18	1
27	4, 4	4	F	None	NA	None	3 PT	2	1	-	-	-	-	-	-	SC × 2 wk	2	1
28	5	12	F	Turning head during sleep	1 d	None	3	-	-	-	-	-	-	-	-	-	-	No FU
29	5	14	F	Down syndrome	None	None	4	10	2	-	-	-	-	-	-	PH × 6 wk/SC, PT	8	1

30	5	6	F	ADN	3-4 d	None	4	2	1	-	-	-	-	-	-	SC × 3 wk, PT	8	1
31	5	5	F	Pharyngitis	3-4 d	None	3	-	1	-	-	-	-	-	-	SC × 2 wk	8	1
32	5	7	M	Lymphadenitis	4 wk	PT	4	7	1	-	-	-	-	-	-	HC × 6 wk	20	1
33	5	6		ADN	None	None	4	3	1	-	-	-	-	-	-	HC × 6 wk, PT	6	1
34	5	6	F	Serving tennis	4 wk	None	3	10	1	-	-	-	-	-	-	-	1.5	No FU
35	5	9	M	URI	2 d	None	4	7	3	4	3	1	-	-	-	PH × 8 wk	10	1

All patients had neck pain, torticollis, and a normal neurologic examination. Clinical information includes age, gender, historical features, delay to presentation, previous treatment, treatment course and duration, immobilization, results and follow-up. Delay: Time from symptoms to evaluation in days; HC: Hard cervical collar; SC: Soft cervical collar; CTO: Cervicothoracic orthosis; PT: Physical therapy; AND: Adenoidectomy; URI: Upper respiratory infection; Treatment: 1: Analgesic with or without an antibiotic; 2: Analgesic, muscle relaxant, with or without an antibiotic; 3: Soft or hard collar; analgesic, muscle relaxant with or without an antibiotic; 4: Admission, skin traction, analgesics, muscle relaxant; 5: Skeletal traction; 6: C1-C2 arthrodesis; Results of treatment: 1: Resolved; 2: Persistent; 3: Relapse; Final results: 1: Asymptomatic, normal activities; 2: Persistent tilt, no pain, no other symptoms; 3: Persistent torticollis, pain and/or other symptoms.

normal rotation to either side ranges from 29° to 45°[5,13,25,26]. As a loss of contact between the C1 and C2 facets of up to 85% occurs at the extremes of physiologic rotation, subluxation is a normal finding during rotation[13,14]. This has led to the use of a dynamic CT scan as a diagnostic modality[5-7,9,26-28], although diagnostic criteria have yet to be established. Important concerns include how C1 and C2 move relative to one another throughout the arc of rotation (C1-C2 angle or angle of separation) and whether C1 crosses over C2. Mönckeberg *et al*[14] suggested that an angle of separation of less than 36° coupled with facet uncoverage of less than 60% were sufficient for a diagnosis. McGuire *et al*[27] recognized that both the separation angle and crossover of C1 were important, and attempted to classify patients as follows: Ⅰ (normal), Ⅱ (< 15° of separation between C1 and C2, C1 crosses over C2), and Ⅲ (C1-C2 angle is fixed or C1 does not cross over C2). In contrast, several studies have questioned the value of dynamic CT scans. Hicazi *et al*[28] found no significant difference between the presenting and corrected sides in atlantoaxial rotation, the atlanto-dens interval, or the center of rotation. Alanay *et al*[29] found that both the intra-observer and inter-observer reliability were poor.

Pang and Li have developed a classification scheme relative to normative data, encompassing a spectrum from AARF (type Ⅰ), through "pathologic stickiness" (types 2 and 3), and finally to muscular torticollis (type 4)[5-7]. They also defined a diagnostic grey zone in which dynamics may presumably return to normal or progress to one of the more severe forms of the condition. Recognizing the limitations of this retrospective review, our impression is that the classification adequately describes the spectrum of pathology, although it is clear that there was discordance with the radiologist's interpretation in many cases.

Several technical points are worth mentioning. Care should be taken to ensure that the patient's shoulders remain flat in the scanner to avoid a false positive result (rotation occurs through trunk rather than cervical spine). It is also prudent to remove the metal arc from the head frame, as this may restrict the active or passive range of cervical rotation. As rotation may also be limited by pain or muscle spasm, some have suggested that the study be performed under sedation, or even general anaesthesia[11,14]. While the 3 data points required to construct a line for the graph can be obtained even with a relatively limited arc of motion, it is possible for example that with greater rotation towards the corrected side, that a patient with type Ⅱ dynamics could achieve cross over and be classified as type Ⅲ.

Only 26% of studies in our series fell within the pathologic spectrum (types Ⅰ-Ⅲ), including just two cases of fixed rotatory subluxation, calling into question the indications for obtaining a dynamic CT scan. A number of these were obtained in the emergency room prior to orthopaedic consultation. Recognizing that an early diagnosis improves outcomes, consideration could be given to empiric treatment for patients presenting within several days of symptom onset with characteristic signs and symptoms of atlanto-axial rotatory pathology, reserving the dynamic CT scan for those failing initial management and/or those presenting in a delayed fashion. Although detailed follow-up information was mainly available for those patients with a greater severity of involvement, the majority of patients resolved with non-operative treatment measures. The two patients with a fixed rotatory subluxation had a protracted course, one of whom presented after 6 mo of previous treatment and ultimately required an arthrodesis. The second responded after three courses of traction and 3 mo of additional immobilization in a pinless halo. For patients with type Ⅱ or type Ⅲ dynamics, all but one resolved with treatment. One patient has relapsed on two occasions but has responded to symptomatic treatment, however the long-term prognosis remains uncertain. We found that all but two patients with normal dynamics or who were classified as being in the diagnostic grey zone resolved clinically, and records were unavailable for the other two. These clinical observations are consistent with a majority of studies[8,16,18,20,27-31].

There are several limitations of this study to be discussed, including the fact that the intra and inter-observer reliability of this scheme has not been reported. We attempted to minimize variations by having each study graded by three examiners, who then reviewed each study together prior to assigning a final class. From a technical standpoint, our scans were obtained in neutral and maximal voluntary rotation to the right and left, in contrast to Pang and Li who obtain their studies at the position of comfort (rotated to right or left), neutral, and toward the opposite or corrected side. Our angle of rotation towards the presenting side might be slightly greater than their "presenting" position, altering one data point on the graph. While our angle of divergence might be slightly greater for the "presenting" side, this should have minimal if any impact on classification. Our follow-up period was limited for all but the most severe cases, and we cannot provide a detailed quantitative assessment of cervical range of motion or of clinical outcomes. Our impression supports previous studies in suggesting that the vast majority of cases resolve without chronic residua. We have not routinely obtained dynamic CT scans after clinical resolution, and cannot prove that normal dynamics were restored in patients who resolved clinically. Persistent abnormalities in rotatory dynamics may be compensated for by an increase in motion at the occiput-C1 articulation or through the subaxial spine.

COMMENTS

Background

Atlantoaxial rotatory displacement represents a spectrum of rotational malalignment between C1 and C2, and Pang and Li have described a classification scheme which explains this spectrum, based on dynamic computed tomography (CT) imaging. The authors classified a group of patients presenting with painful torticollis according to Pang and Li and compared findings with the interpretation by the authors' radiologists and with each patient's clinical course.

Research frontiers

There is limited information in the literature on atlantoaxial rotatory displacement, and a variety of terms have been utilized to describe the condition, suggesting that there is a need for a common language to describe the pathology.

Innovations and breakthroughs

There are few studies concerning the Pang and Li classification, and while this classification is able to capture a spectrum of pathology, it has not achieved wide clinical use to our knowledge. The authors sought to determine whether the Pang and Li class correlated with our radiologist's interpretation of dynamic rotational CT scans.

Applications

The Pang and Li classification has practical applications and may be used by the clinician to characterize the findings on a dynamic CT scan. The findings allow the clinician to be more specific in articulating the nature of the pathology.

Terminology

Atlantoaxial rotatory displacement: Abnormal relationship between C1 and C2 in the axial plane in which there may or may not be mobility between the two segments; Atlantoaxial rotatory subluxation: abnormal relationship between C1 and C2 in the axial plane in which there is mobility between the two vertebrae; Atlantoaxial rotatory fixation: fixed abnormal relationship between C1 and C2 in the axial plane.

Peer-review

The current study focused on an original issue. It is well-organized.

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P- Reviewer: Cartmell S, Erkan S, Peng BG, Rothschild BM
S- Editor: Ji FF **L- Editor**: A **E- Editor**: Lu YJ

World Journal of Orthopedics

Submit a Manuscript: http://www.f6publishing.com

World J Orthop 2017 November 18; 8(11): 846-852

DOI: 10.5312/wjo.v8.i11.846

ISSN 2218-5836 (online)

ORIGINAL ARTICLE

Randomized Controlled Trial

Hypothenar fat pad flap *vs* conventional open release in primary carpal tunnel syndrome: A randomized controlled trial

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Clinical trial registration statement: This study is registered at www.clinicaltrials.in.th. The registration identification number is TCTR20170719002.

Informed consent statement: All study participants provided informed written consent prior to study enrollment.

Conflict-of-interest statement: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Manuscript source: Unsolicited Manuscript

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Received: January 23, 2017
Peer-review started: February 2, 2017
First decision: June 26, 2017
Revised: July 10, 2017
Accepted: September 3, 2017
Article in press: September 4, 2017
Published online: November 18, 2017

Abstract

AIM

To compared outcomes between the hypothenar fat pad flap (HTFPF) and conventional open carpal tunnel release (COR) in primary carpal tunnel syndrome (CTS).

METHODS

Forty-five patients (49 hands) were enrolled into the study from January 2014 to March 2016, 8 patients were excluded. Randomization was conducted in 37 patients (41 hands) by computer generated (Block of four randomization) into COR and HTFPF group. Nerve conduction study (NCS) included distal sensory latency (DSL), distal motor latency (DML), sensory amplitude

(S-amp), motor amplitude (M-amp) and sensory nerve conduction velocity (SCV) were examined at 6 and 12 wk after CTR. Levine score, grip and pinch strength, pain [visual analog scale (VAS)], 2-point discrimination (2-PD), Semmes-Weinstein monofilament test (SWM), Phalen test and Tinel's sign were evaluated in order to compare treatment outcomes.

RESULTS

The COR group, 19 patients (20 hands) mean age 50.4 years. The HTFPF group, 20 patients (21 hands) mean age 53.3 years. Finally 33 patients (36 hands) were analysed, 5 patients were loss follow-up, 17 hands in COR and 19 hands in HTFPF group. NCS revealed significant difference of DSL in HTFPF group at 6 wk (P < 0.05) compared with the COR group. S-amp was significant improved postoperatively in both groups (P < 0.05) but not significant difference between two groups. No significant difference of DML, M-amp and SCV postoperatively in both groups and between two groups. Levine score, pain (VAS), grip and pinch strength, 2-PD, SWM, Phalen test and Tinel's sign were improved postoperatively in both groups, but there was no significant difference between two groups.

CONCLUSION

There is no advantage outcome in primary CTS for having additional HTFPF procedure in CTR. COR is still the standard treatment. Nevertheless, improvement of DSL and S-amp could be observed at 6 wk postoperatively.

Key words: Hypothenar fat pad flap; Randomized controlled trial; Carpal tunnel release; Carpal tunnel syndrome; Nerve conduction study

Core tip: The study conducted a randomized controlled trial to compare between the hypothenar fat pad flap additional and conventional open carpal tunnel release in primary carpal tunnel syndrome. The study showed no advantage, however improvement of nerve conduction study was observed in the early postoperatively.

Kanchanathepsak T, Wairojanakul W, Phakdepiboon T, Suppaphol S, Watcharananan I, Tawonsawatruk T. Hypothenar fat pad flap *vs* conventional open release in primary carpal tunnel syndrome: A randomized controlled trial. *World J Orthop* 2017; 8(11): 846-852 Available from: URL: http://www.wjgnet.com/2218-5836/full/v8/i11/846.htm DOI: http://dx.doi.org/10.5312/wjo.v8.i11.846

INTRODUCTION

Carpal tunnel syndrome (CTS) is the most common compression neuropathy in the upper extremity[1]. The worldwide incidence is 5.8% in women and 0.6% in men[2], while the pathology and the causes are unclear. Several studies describe that the symptoms caused by direct nerve compression and nerve ischemia[3,4].

Fullerton[4] found that the numbness symptom of CTS may arise from the nerve ischemia. The median nerve ischemia alters axonal threshold and significantly increases both sensory and motor refractoriness resulting numbness and paresthesia in CTS patients[3]. Furthermore, the nerve ischemia may cause by venous return obstruction dued to external pressure that increases pressure in the region of entrapment, leading to nerve edema and eventually resulting in nerve damage and fibrous tissue[5,6] and also can be provoked by ganglia, neoplastic masses, vascular abnormalities, ligamentous attachments, and also different various structures (anomalous muscles, bifid median nerve, persistent median artery)[7].

Carpal tunnel release (CTR) is a standard treatment for patients who indicated to surgery of CTS and the success rate was 75%-98%. However, several studies[8] found that some patients who had persist or recurrent compressive symptoms after this surgery was as high as 2%-25%. Nancollas *et al*[9], a retrospective review of 60 cases with an average of 5.5 years follow-up, had reported 57% recurrent symptoms within 2 years after surgery.

The hypothenar fat pad flap (HTFPF) procedure, first described by Cramer and refined by Strickland *et al*[10] is usually utilized in recurrent CTS, there is a adipose tissue from hypothenar eminence as a pedicle flap to cover the median nerve that provides vascularity, enhance nerve gliding property and prevent adhesion to the median nerve. This procedure had an excellent result and low rate of complication[8,10,12]. We hypothesized that increasing vascularity to the median nerve by HTFPF procedure could improve the nerve recovery and the success rate of CTR in primary CTS compared to the conventional CTR alone.

MATERIALS AND METHODS

Forty-five patients (49 hands) who diagnosed with primary carpal tunnel syndrome were enrolled into the study during January 2014 and March 2016 while 8 of them were excluded from the study. Thirty-seven patients (41 hands) were conducted in this prospective randomized controlled trial study according to consort diagram (Figure 1). The study was approved by the local institutional review board and all patients signed an informed consent.

The inclusion criteria were primary idiopathic carpal tunnel syndrome, age 20-60 years, duration of symptoms at least 3 mo and no improvement of symptoms after conservative treatment. The exclusion criteria were previous CTR or trauma in affected hand, history of steroid injection, cerebrovascular disease, cervical radiculopathy, combined other nerve compression, diabetes mellitus, cognitive impairment and unwilling to participate.

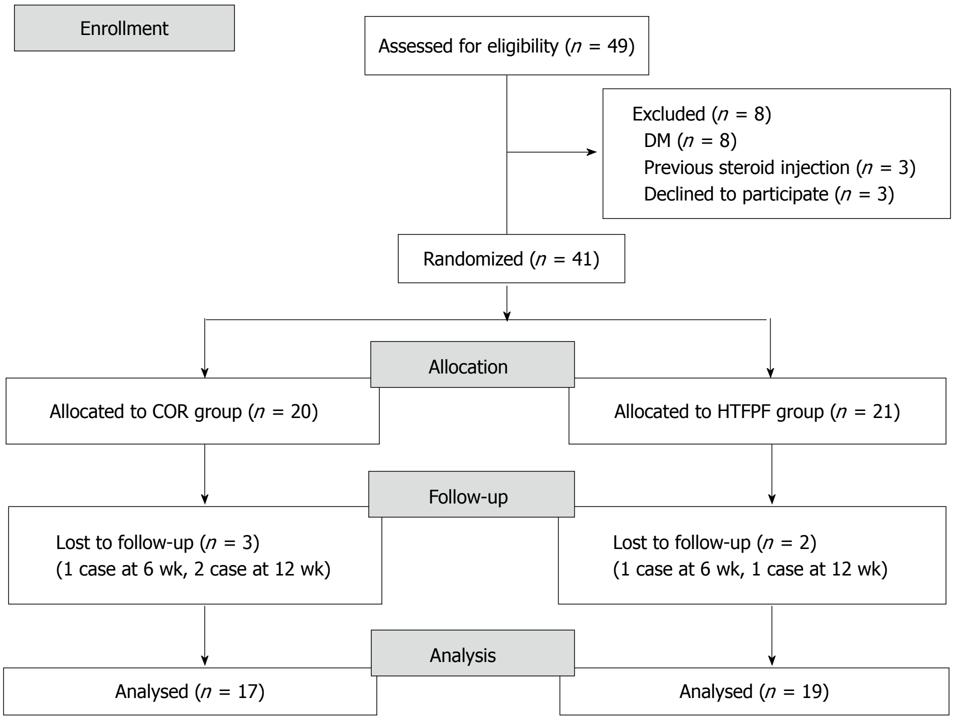

Figure 1 Consort flow diagram showed the randomization process. COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

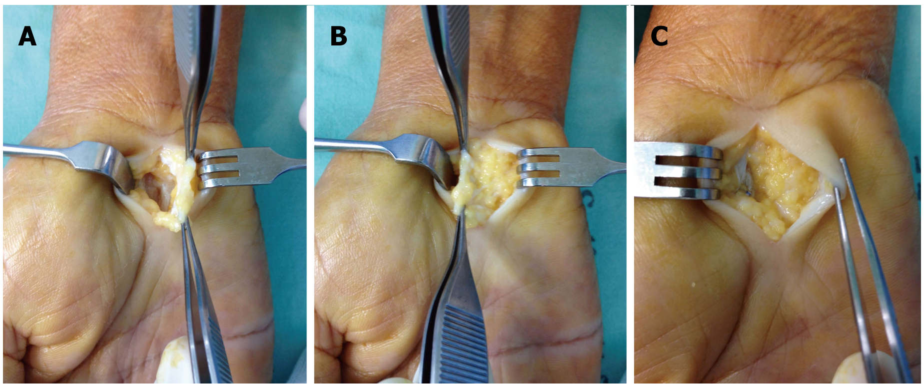

Figure 2 Transverse carpal ligament was exposed. A: Dissecting the hypothenar fat pad after complete released of transverse carpal ligament (TCL); B: Harvested hypothenar fat pad flap (HTFPF) was prepared to cover the median nerve; C: HTFPF was sutured to radial half of TCL remnant and covered the median nerve.

Patients were randomized into either conventional open carpal tunnel release group (COR) or HTFPF group by using a computer generated table, STATA 12.0, Statacorp, college station, TX, United States (Block of four randomization) and concealed with sealed envelopes which were opened during the operation after transverse carpal ligament was released. All of the patients and assessors in this study were blinded after the interventions assignment.

Surgical technique

The only one senior hand surgeon performed CTR throughout the study. All patients were injected with 1% lidocaine without adrenaline for local anesthesia. A tourniquet was inflated 250 mmHg. Longitudinal skin incision was made from distal to the distal wrist flexion crease and 5 mm ulnar to thenar crease along the Kaplan's line about 3 cm in length. Subcutaneous tissue and palmar fascia were dissected and retracted by Ragnel retractors. The transverse carpal ligament (TCL) was exposed and released by Stevens tenotomy scissors until clearly identified the median nerve (Figure 2A).

The concealed envelopes were opened to allocate the group of patients. In COR group, normal saline was irrigated and skin sutured with nylon no 5-0. In HTFPF group, superficial dissection at hypothenar fat was performed deep to palmaris brevis muscle and care should be taken to avoid digital nerve injury of ring and small fingers. The hypothenar fat pad with its vascular from ulnar artery was harvested (Figure 2B) then sutured HTFPF to radial half of TCL remnant

Table 1 Demographics data of conventional open carpal tunnel release and hypothenar fat pad flap groups

	COR group (n = 17)	HTFPF group (n = 19)	P value
Age (yr) mean ± SD	50.4 (1.5)	53.3 (1.5)	0.182
Gender (%)			0.231
Male	0 (0)	2 (11)	
Female	17 (100)	17 (89)	
Body mass index mean ± SD	28.4 (1.3)	25.5 (0.9)	0.064
Hand dominant (%)			1
Right	15 (88)	17 (90)	
Left	2 (12)	2 (10)	
Side of operation (%)			0.017
Right	6 (35)	15 (79)	
Left	11 (65)	4 (21)	
Onset of duration mo mean ± SD	11.8 (2.3)	13.3 (2.5)	0.675

COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

with absorbable suture material for coverage over the median nerve (Figure 2C). Normal saline was irrigated and skin was sutured with nylon no 5-0. Wound dressing was applied in both groups.

All of patients were followed up 6 and 12 wk after surgery and nerve conduction study (NCS), physical examination, pain [visual analog scale (VAS)], symptom severity scale and functional status scale (Boston questionnaire) were recorded at each visit. Sutured was removed 2 wk after surgery in all patients.

Study factors and measurements

The primary outcome was NCS including distal sensory latency (DSL), sensory amplitude (S-amp), distal motor latency (DML), motor amplitude (M-amp) and sensory conduction velocity (SCV). Self-administered questionnaire described by Levine *et al*[13], which also known as Boston questionnaire was used to evaluate the hand function. Boston questionnaire consists of symptom severity scale (SSS) which includes 11 questions which each answer score from 1 (best) to 5 (worst), making a total score of 55 and functional status scale (FSS) which includes 8 questions which each answer score from 1 (best) to 5 (worst), making total score 40.

Age, gender, body mass index (BMI), onset of duration, side of operation and hand dominant were collected. Pain (visual analog scale, VAS), Tinel's sign, Phalen test, grip strength, pinch strength, 2-point discrimination (2-PD), Semmes-Weinstein monofilament test (SWM) and complication were evaluated in all patients.

NCS, pain (VAS), Levine score and all examination were compared between two groups at preoperatively, and 6 and 12 wk postoperatively. The NCS was performed as described in the previous literature[17] by the same physician.

Statistical analysis

The demographic data including age, gender, BMI, onset of duration, side of operation, hand dominant and examination (Tinel's sign and Phalen test) were collected with excel version 2013. All of the continuous data were normally distributed and were presented with mean ± SD, while the categorical data were shown in percentage.

The primary and secondary outcomes were analyzed with the repeated ANOVA and Graphpad software version 6.0 and the relationship between groups and time to follow-up were evaluated. These data include NCS, Levine score, pain (VAS), 2-PD, grip strength, pinch strength and SWM. $P < 0.05$ was used to determine the correlation between two groups and time to follow-up postoperatively.

RESULTS

The COR group consists of 19 patients (20 hands, n = 20), all were female with the mean age of 50.4 years (41-62 years). The HTFPF group consists of 20 patients (21 hands, n = 21); 2 males (11%) and 16 females (89%) with the mean age of 53.3 years (42-63 years). Five patients were lost to follow-up; 3 cases in COR group and 2 cases in HTFPF group. Finally 33 patients (36 hands) were analysed in this study with 17 hands in COR group and 19 hands in HTFPF group. The demographic data of the included patients are summarized in Table 1.

NCS revealed the improvement of DSL in HTFPF group at 6 and 12 wk postoperatively and statistically significant difference at 6 wk ($P < 0.05$) comparing with the COR group (Figure 3). S-amp was statistically significant improved postoperatively in both groups ($P < 0.05$) but not significantly different between two groups (Figure 4). There were no statistically significant differences of DML, M-amp and SCV between preoperative and postoperative in both groups and no statistically significant different of DML, M-amp and SCV between two groups (Figures 5-7).

Postoperative pain (VAS) was decreased in both groups but there was no significantly different between two groups. Negative result in both Tinel's sign and Phalen test were detected in both groups postoperatively. Grip strength, pinch strength, 2-PD, SWM and Levine

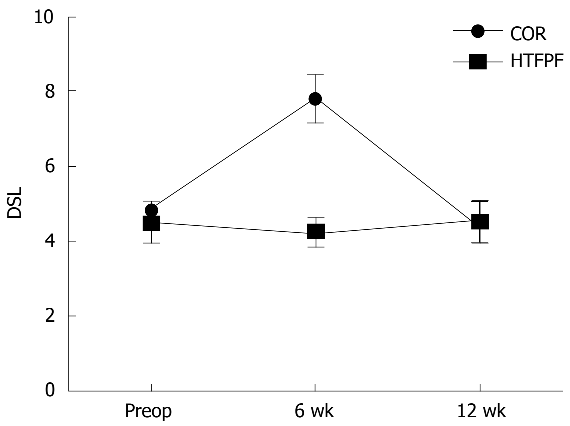

Figure 3 Distal sensory latency was significantly improved in hypothenar fat pad flap group at 6 wk postoperatively, *P* < 0.05, but not significant different in between groups at 12 wk postoperative. DSL: Distal sensory latency; COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

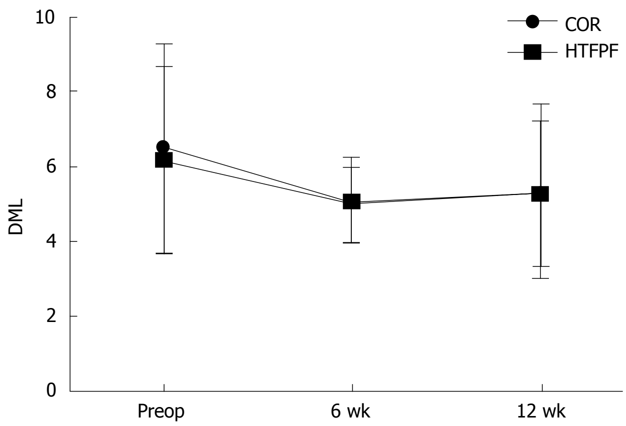

Figure 5 Distal motor latency was not significantly improved post-operatively in both groups and not significant different in between groups. DML: Distal motor latency; COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

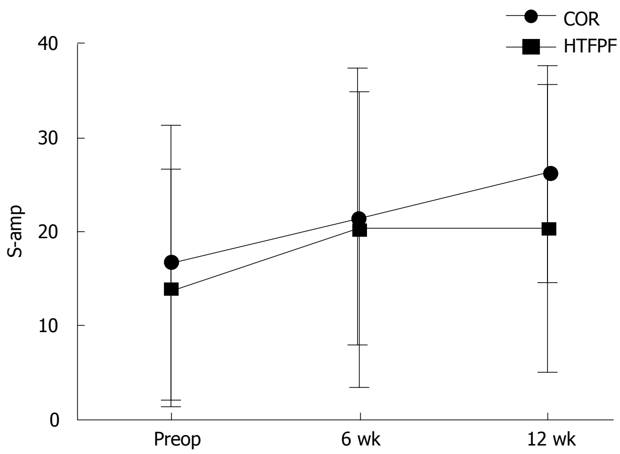

Figure 4 Sensory amplitude was significantly improved in both groups postoperatively. S-amp: Sensory amplitude; COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

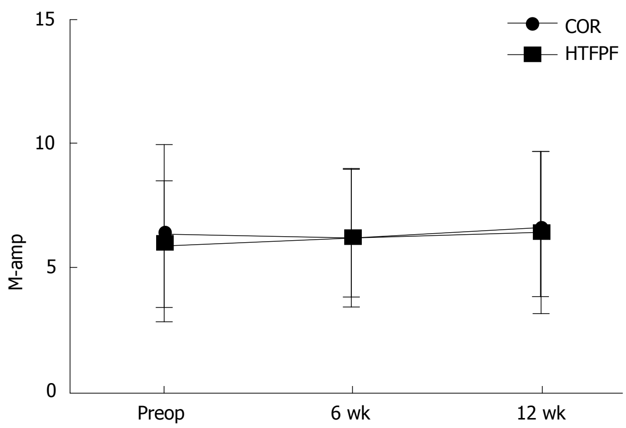

Figure 6 M-amp was not significantly improved postoperatively in both groups and not significant different in between groups. M-amp: Motor amplitude; COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

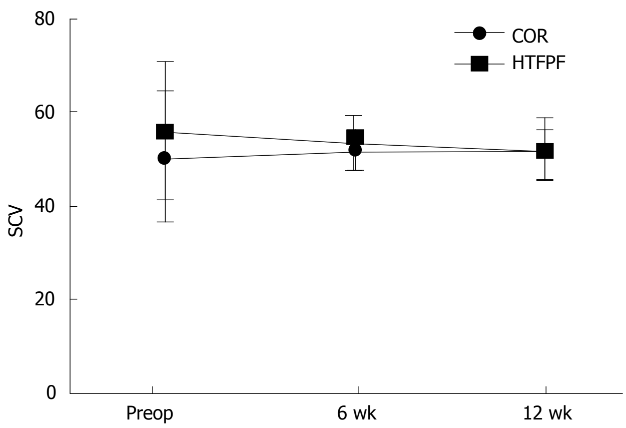

Figure 7 Sensory nerve conduction velocity was not significantly improved postoperatively in both groups and not significant different in between groups. SCV: Sensory nerve conduction velocity; COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

score were improved in both groups, however there was no statistical difference between two groups was shown (Tables 2-4).

At 6 wk after operation, painful scar was occurred 11.76% and 31.58% in COR and HTFPF groups respectively, eventually the symptom was resolved in both groups at 12 wk and there were no statistically significant difference between two groups. Two of 19 cases in HTFPF group had pain over hypothenar eminence at 6 wk, however this symptom was disappeared at 12 wk.

DISCUSSION

The HTFPF is vascularized pedicle flap that supplied by branches of ulnar artery and widely used for recurrent or persistent CTS with median nerve hypersensitivity. Most authors reported an excellent result of HTFPF[8,10-12], even though had some modification by Craft *et al*[12] suggested the combination of microneurolysis of the median nerve and HTFPF.

It is limited evidence in the flap coverage procedure on the median nerve in primary CTS. Increasing vascularity to the median nerve may result in rapid

Table 2 Results of levine score

Levine score	Preop., mean ± SD		6 wk postop., mean ± SD		12 wk postop., mean ± SD		*P* value
	COR	HTFPF	COR	HTFPF	COR	HTFPF	
Symptom severity scale	2.6 (0.6)	2.5 (0.5)	1.7 (0.5)	1.7 (0.5)	1.5 (2.5)	1.1 (0.1)	> 0.05
Functional status scale	2.4 (1.0)	2.5 (0.9)	1.8 (0.7)	1.7 (0.6)	1.4 (0.6)	1.1 (0.2)	> 0.05

COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

Table 3 Results of grip and pinch strength

	Preop., mean ± SD		6 wk postop., mean ± SD		12 wk postop., mean ± SD		*P* value
	COR	HTFPF	COR	HTFPF	COR	HTFPF	
Grip strength (Pound)	29.2 (15.0)	28.9 (14.1)	22.3 (12.8)	21.4 (10.4)	30.4 (13.0)	31.4 (10.8)	> 0.05
Pinch strength (Pound)	12.0 (3.3)	11.9 (3.9)	11.0 (2.8)	11.5 (3.4)	13.3 (3.3)	15.5 (3.0)	> 0.05

COR: Conventional open release; HTFPF: Hypothenar fat pad flap.

Table 4 Results of pain (Visual analog scale), 2-point discrimination and semmes-weinstein monofilament

	Preop., mean ± SD		6 wk postop, mean ± SD		12 wk postop, mean ± SD		*P* value
	COR	HTFPF	COR	HTFPF	COR	HTFPF	
Pain (VAS)	4.6 (3.4)	4.4 (3.4)	0.4 (1.0)	0.5 (1.1)	0 (0)	0 (0)	> 0.05
2-PD (mm)	3.5 (1.0)	4.7 (2.9)	3.1 (0.8)	2.9 (0.7)	2.5 (0.5)	2.7 (0.8)	> 0.05
SWM	3.7 (0.3)	4.1 (1.0)	3.4 (0.4)	3.4 (0.5)	3.3 (0.4)	3.1 (0.4)	> 0.05

COR: Conventional open release; HTFPF: Hypothenar fat pad flap; VAS: Visual analog scale; 2-PD: 2-point discrimination; SWM: Semmes-weinstein monofilament.

nerve recovery and improve success rate. For that reason this study was conducted to add this procedure during CTR. This study used NCS for detection of nerve electrophysiology in short-term follow-up since there was no difference in the outcome of mid-term and long-term follow-up[9,14].

The advantage of HTFPF procedure are well-vascularized pedicle flap, could be harvested from same incision use of CTR with no donor site morbidity and sufficient to cover the median nerve in carpal tunnel[10,15].

The result of NCS revealed better nerve recovery in DSL in HTFPF group at 6 wk but not different at 12 wk compared to COR group. The S-amp was improved after surgery in both groups, however no significant difference between two groups was observed. There was no advantage outcomes of HTFPF procedure compared to COR in primary CTS. There were few studies performed the NCS in early postoperative, however this study shows an early detect of the electrophysiological conduction change in median nerve. This result was similar to study of Ginanneschi *et al*[14] reported at one month after CTR, SCV and DML were improved.

Conversely, El-Hajj *et al*[16] compared the DML and DSL, M-amp and S-amp, and SCV preoperatively and postoperatively, the result showed an improvement in all studied variables, except the DSL at 18 wk after surgery which improved only at 42 wk. The author explained that recovery of the sensory was delayed compare to motor, because the sensory fibers were affected more than motor fibers, and the myelin sheath more than the axons in most cases of CTS. Tahririan *et al*[17] study showed significant improvement in DSL, DML and SCV 6 mo postoperatively.

The strength of this study is the prospective randomized controlled trial, while small number of cases in each group is the limitation. Increased risk of painful scar and pain over the hypothenar eminence was found in HTFPF group. However, there was no statistical difference between two groups.

This study concluded that there was no advantage outcome in primary CTS for having additional HTFPF procedure in CTR compared with conventional technique. COR is still the standard treatment in primary CTS. Nevertheless, improvement of DSL and S-amp could be observed at 6 wk postoperatively. However, the interesting point is the recurrent rate in long-term follow-up between two groups and further data collection and analysis should be carried out in the future.

COMMENTS

Background

Carpal tunnel syndrome is the most common compression neuropathy. Carpal tunnel release is a standard treatment for patient who indicated for surgery although complete nerve recovery was not achieved for all of patients. This study hypothesized that increasing vascularity to the median nerve by hypothenar fat pad flap procedure could improve the nerve recovery of carpal tunnel release in primary carpal tunnel syndrome.

Research frontiers

Many recent studies used flap coverage procedure on the median nerve for recurrent or persistent carpal tunnel syndrome.

Innovations and breakthroughs

There is no other studies have done the comparison between hypothenar fat pad flap and conventional carpal tunnel release in primary carpal tunnel syndrome before.

Applications

Although no advantage outcome in primary carpal tunnel syndrome for having additional hypothenar fat pad flap procedure in carpal tunnel release. However, improvement of distal sensory latency and sensory amplitude could be observed at 6 wk postoperatively.

Terminology

Hypothenar fat pad flap is vascularized pedicle flap that supplied by branches of ulnar artery.

Peer-review

It is a well presented prospective randomized controlled trial comparing the hypothenar fat pad flap with conventional open techniques for carpal tunnel syndrome.

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