Medical Engineering and Physics 39 (2017) 83–93

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

# Biomechanical analysis of combining head-down tilt traction with vibration for different grades of degeneration of the lumbar spine

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ARTICLE INFO

*Article history:*
Received 4 October 2015
Revised 31 August 2016
Accepted 23 October 2016

*Keywords:*
Head-down tilt (HDT) traction
Vibration
Degeneration
Lumbar spine
Finite element analysis (FEA)

ABSTRACT

In recent years, a combination of traction and vibration therapy is usually used to alleviate low back pain (LBP) in clinical settings. Combining head-down tilt (HDT) traction with vibration was demonstrated to be efficacious for LBP patients in our previous study. However, the biomechanics of the lumbar spine during this combined treatment is not well known and need quantitative analysis. In addition, LBP patients have different grades of degeneration of the lumbar spinal structure, which are often age related. Selecting a suitable rehabilitation therapy for different age groups of patients has been challenging. Therefore, a finite element (FE) model of the L1–L5 lumbar spine and a vibration dynamic model are developed in this study in order to investigate the biomechanical effects of the combination of HDT traction and vibration therapy on the age-related degeneration of the lumbar spine. The decrease of intradiscal pressure is more effective when vibration is combined with traction therapy. Moreover, the stresses on the discs are lower in the "traction + vibration" mode than the "traction-only" mode. The stress concentration at the posterior part of nucleus is mitigated after the vibration is combined. The disc deformations especially posterior disc radial retraction is improved in the "traction + vibration" mode. These beneficial effects of this therapy could help decompress the discs and spinal nerves and therefore relieve LBP. Simultaneously, patients with grade 1 degeneration (approximately 41–50 years old) are able to achieve better results compared with other age groups. This study could be used to provide a more effective LBP rehabilitation therapy.



## 1. Introduction

At some point in their lives, 85% of the population, especially females and those aged 40-80 years, will experience low back pain (LBP), which can induce decreased functional capacity of the spine, muscle strength and endurance and other issues [1–4]. According to a systematic review of global prevalence of LBP in 2012, the highest prevalence of LBP appears during middle age, which represents some of the most productive years of a person's working life. This high prevalence of LBP may bring negative effects on economic conditions for individuals, families and industrial companies [2]. Research has indicated that LBP mainly results from the protrusion of intervertebral disc [5]. Moreover, the degeneration of an intervertebral disc reportedly causes LBP as well [6]. Traction beds were used to treat scoliosis, backaches and spinal deformities since the early 19th century. As one of the most common traction therapy devices, they act to relive LBP and recover joint functions by decompressing discs or nerves by applying primary load along the inferior-superior axis of the spine [7–9]. Meanwhile, low-frequency vibration was reported to be helpful for increasing the lower limb strength, balance and muscular performance [10–12]. In recent years, traction and vibration have been commonly combined to relieve LBP in clinical settings [13,14]. In our previous study, electromyography (EMG) of 30 patients was recorded to evaluate the effect of the combination of traction and vibration therapy on erector spinae. We concluded that combining head-down tilt (HDT) traction (tilt angle: 20°) with vibration (waveform: sinusoidal, amplitude: 50 mm, footrest vibration frequency: 3.5 Hz, electrical motor vibration frequency: 12 Hz at the same time, thus the working mode of the spine combining bed we study in this research keeps consistent with what we reported before [15]) could obtain better effects for the fatigue of lower muscle in LBP patients compared to traction alone [15]. However, the biomechanism of combining HDT traction and vibration therapy to relieve LBP is not clear now and should be quantitatively analyzed.

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http://dx.doi.org/10.1016/j.medengphy.2016.10.004
1350-4533/

In addition, LBP patients have different grades of degeneration of the lumbar spinal structure, which are age related [16,17]. A new term age-sensitivity has been introduced by Kurutz to describe the elongation capacity decrease of 0.01–0.04 mm/year per year of aging [18]. Kurutz analyzed the age-sensitivity of time-related in vivo deformability of human lumbar spine in centric tension. Kurutz reported that, for degenerated lumbar segments in L3-S1, age sensitivity was about−0.01 mm/year in the elastic phase and increased to about −0.035 mm/year in the final viscoelastic phase [18]. The patient's age significantly influences the mechanical properties of the lumbar spine units. We want to investigate the curative effect of the combination of HDT traction and vibration therapy on different grades of degeneration of the lumbar spine. Selecting a suitable rehabilitation therapy for different age groups of LBP patients remains a challenge. Therefore, different degeneration grades (0–4) of the lumbar spine are introduced in this study.

Numerical simulation is one of the most effective and commonly used methods to quantitatively evaluate the effect of rehabilitation therapy in terms of biomechanics [19,20]. Kurutz and Oroszvary analyzed the biomechanical effects of weightbath hydrotraction therapy for treating degenerative diseases of lumbar spine using age-related degenerated finite element (FE) models (L1–L5) [19]. They first time reported the deformations and stresses of intervertebral discs in axial tension load during the weightbath hydrotraction therapy. Park et al. investigated the biomechanical effects of two-step traction therapy, which included global axial traction and local decompression, on the lumbar spine using a FE model of the lumbar spine (L1–S1) [20]. They reported the decrease of the tensile stress on the fibers of the annulus fibrosus and reduction in intradiscal pressure as well. The benefit of the FE analysis approach is that it can provide the detailed stresses on the fibers of annulus fibrosus and ligaments and detailed intradiscal pressure, because these values are difficult to measure in vivo without damaging the soft tissues. Therefore, a three-dimensional (3D) FE model of the lumbar spine (L1–L5), including five grades of degeneration, is developed in this work for FE analysis.

The aim of this study is to investigate the biomechanism of the combination of HDT traction and vibration therapy for relieving LBP. The changes of the intradiscal pressure, stresses of the intervertebral discs, disc deformations and stresses of ligaments for different grades of degeneration of the lumbar spine will be determined during the traction and vibration combined therapy. The results of this study could provide a theoretical basis for therapy selection in future clinical practice.

## 2. Methods

### 2.1. Development of the FE model of the L1–L5 lumbar spine

The L1–L5 vertebrae was reconstructed in a medical image processing software (Mimics 10.0, Materialise Technologies, Belgium) based on CT images of a healthy 38 years old male (height: 175 cm, weight: 68 Kg). The intervertebral discs were generated in a CAE pre-processing software (Hypermesh 11.0; Altair Engineering Corp, USA). Then, a 3D FE model of the L1–L5 lumbar spine was built in the software of Abaqus 6.11-1 (HKS, Hibbit, Karlsson & Sorenson Inc. USA). The lumbar spine model included five vertebrae (L1–L5), four intervertebral discs and seven ligaments (interspinous ligament (ISL), supraspinous ligament (SSL), anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), ligamentum flavum (LF), capsular ligament (CL) and intermuscular transverse ligament (ITL)). As shown in Fig. 1a, a vertebra consisted of a vertebral body and posterior elements; the vertebral body was made up of bony endplate, cortical bone and cancellous bone. The cortical bone was modeled as a 0.35 mm thick shell surrounding the cancellous core. The thickness of the endplate was assumed to be 0.5 mm. All components of the vertebra were modeled as hexahedral solid elements. The facet joints were processed as nonlinear contact. The intervertebral disc was developed as a nucleus pulposus surrounded by an annulus fibrosus, and the nucleus pulposus was determined to be approximately 44% of the total disc volume. The annulus fibrosus consisted of matrix (annulus ground substance) and fibers. There were six layers of fibers surrounding the annulus matrix. The nucleus and annulus matrix were modeled as hexahedral solid elements. The annulus fibers were modeled as truss elements which only experienced tension and arranged at an angle about ±30° from the endplates. The ligaments were developed using tension-only truss elements.

Table 1 showed the material properties of the healthy lumbar spine units. Linear elastic isotropic materials were used for the vertebral body, posterior elements and endplates [21–23]. A fluid-like, isotropic, incompressible, elastic material was used for the nucleus [19,24]. The annulus matrix was set to linear elastic materials in both compression and tension state [19,24]. Linear elastic isotropic tension-only material was used for the annulus fibers, and the stiffness of the fibers increased outward to simulate their different types of radial variation and the contents of collagen in fibers [19,21,25]. Linear elastic tension-only material was used for ligaments [19,22]. The cross sectional area of each ligament in Table 1 was cited from published literatures [24,26]. The density values of L1–L5 units were listed in Table 1 to represent the mass of the L1–L5, which were obtained from the literature [24].

It was reported that the degeneration of intervertebral discs would result in LBP [6]. Meanwhile, the degeneration was correlated with aging significantly [16–19]. Degeneration could generally induce changes of disc structure as aging, which was called age-related degeneration [19,25]. The age-related degeneration of discs was mainly reflected in the dehydration process, which led to drier and harder components of nucleus [16,19,27]. Five grades of degeneration were first introduced by Kurutz [19]. The changes of the values of material properties were used to simulate the different degeneration grades, and we obtained these values from the literature [19]. As described in Table 2, the dehydrated state in the nucleus was simulated by decreasing Poisson's ratio; the hardening process in the nucleus and annulus matrix was modeled by increasing Young's modulus. Only the tension material properties were used in our model because of the traction loading condition. Grade 0 (healthy) to 4 (fully degenerated) corresponded approximately to the following age ranges: <40, 41–50, 51–60, 61–70 and >70 years, respectively (Table 2). The correlation between five grades of degeneration and five age groups was derived from research by Kurutz et al [18,19].

### 2.2. Spine combining bed working modes

The spine combining bed was designed for the treatment of back pain combing traction and vibration. Fig. 1b was the schematic view of the spine combining bed. The bed plates of the spine combining bed consisted of 1 fixed plate and 18 suspension plates hanging on the edge of bed by flexible wires (Fig. 1b). The suspension plates were highly moveable because of the flexible wires. The only power source of this bed was the footrest, which was controlled by an electrical motor (vibration frequency: 12 Hz). The footrest could vibrate along *X*-axis. The waveform of the vibration was sinusoidal. The amplitude of the wave was 50 mm and the footrest vibration frequency was 3.5 Hz. In Fig. 1a, the bed tilted to 20° to keep the subject head-down position. The subject laid supine on the bed with soles fixed on the vibration footrest via bandage. The traction load was exerted by the subject's own body weight when tile angle existed. When the footrest started vibrating, the feet of subjects would follow the movement of footrest and the other parts of the body would vibrate as well. When the