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A model for flexi-bar to evaluate intervertebral disc and muscle forces in exercises

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ABSTRACT

This study developed and validated a lumped parameter model for the FLEXI-BAR, a popular training instrument that provides vibration stimulation. The model which can be used in conjunction with musculoskeletal-modeling software for quantitative biomechanical analyses, consists of 3 rigid segments, 2 torsional springs, and 2 torsional dashpots. Two different sets of experiments were conducted to determine the model's key parameters including the stiffness of the springs and the damping ratio of the dashpots. In the first set of experiments, the free vibration of the FLEXI-BAR with an initial displacement at its end was considered, while in the second set, forced oscillations of the bar were studied. The properties of the mechanical elements in the lumped parameter model were derived utilizing a non-linear optimization algorithm which minimized the difference between the model's prediction and the experimental data. The results showed that the model is valid (8% error) and can be used for simulating exercises with the FLEXI-BAR for excitations in the range of the natural frequency. The model was then validated in combination with AnyBody musculoskeletal modeling software, where various lumbar disc, spinal muscles and hand muscles forces were determined during different FLEXI-BAR exercise simulations.

1. Introduction

Low back pain (LBP) is a significant health challenge of epidemic proportions that results in substantial personal, community, and financial burdens, globally. In industrialized countries, LBP has been cited as the second most frequent chronic condition that warrants visiting a doctor, the fifth most common reason for hospitalization, and the third most frequent cause for undergoing a surgical procedure [1]. Examination and treatment of the muscles of the trunk have long been advocated as important parts in the physical therapy of chronic low back pain patients [2–4]. Multiple training exercises and therapeutic devices have been proposed for enhancing trunk muscles' strength and spinal rehabilitation, including bridging, side-bridging, curl-up and birddog exercises [4,5]. In addition, exercises using a Swiss ball, unstable surfaces as well as oscillatory (vibration simulation) exercises have recently been effectively used [6–12]. Oscillatory devices, such as an oscillating pole and Swiss Ball, aim to increase the strength of muscles and consequently the stability by triggering the cyclic activation of the torso muscles [7,8,13,14]. The underlying concept involves the generation of oscillatory movements of the upper extremity, while the torso is braced in order to provide a stable foundation. Vibration stimulation exercises, in particular, are increasingly being introduced in a wide range of rehabilitation and fitness centers for improving muscle strength, coordination, and balance [15]. Despite their growing popularity and word of mouth evidence of effectiveness, oscillatory blades and vibration devices remain not well studied with limited quantitative data to guide their use [11,16].

The FLEXI-BAR® Standard is a training instrument that provides vibration stimulation towards recruiting trunk muscles. It has been used for many years in Germany for rehabilitation purposes, as well as recreational training environments [15]. The underlying principle behind the FLEXI-BAR lies in effectively targeting the deep muscles of the body. The vibrations are created when a shaking action is maintained, triggering a passive response from the

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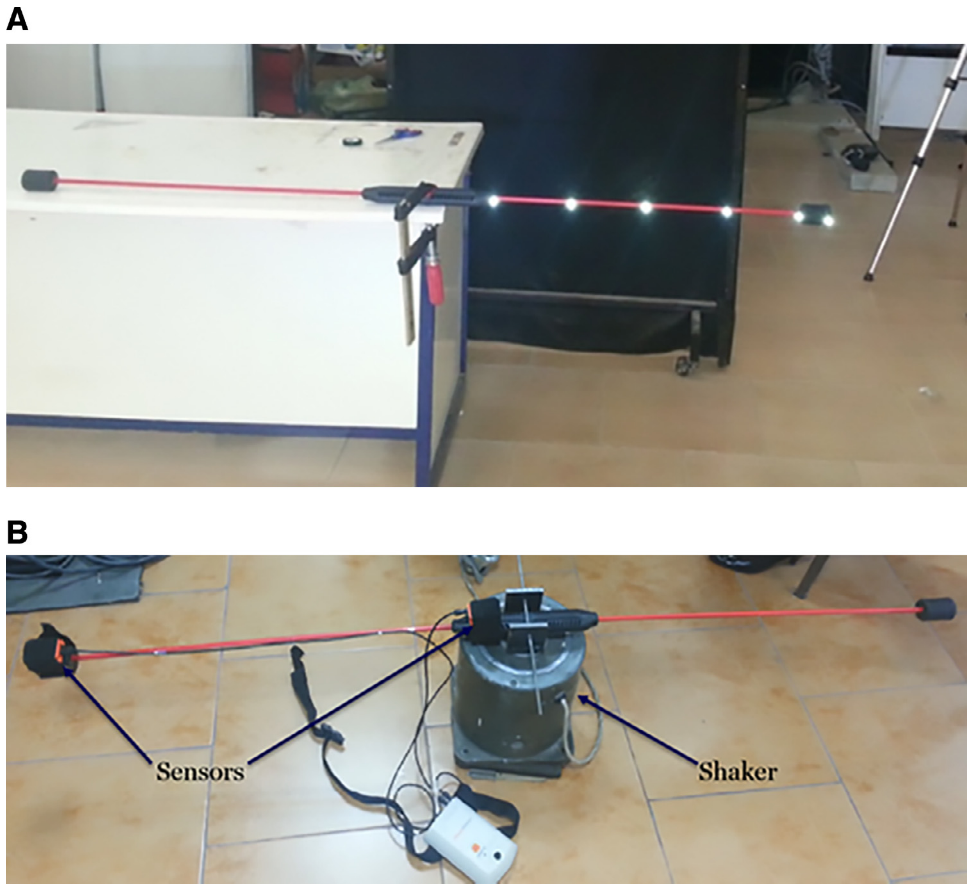

Fig 1. Free (A) and Forced (B) vibration experiments setup.

deep muscles, which allows the agonist and antagonist muscles to work together in response to these vibrations.

A number of studies have investigated the application of the FLEXI-BAR in terms of the activation of various muscle groups [17,18]. Some of these studies compared different exercises using flexible poles with each other according to muscles' activation patterns [9,17–21]. The majority include EMG-based experiments as the main assessment tool for the evaluation of muscles activities, where a specific exercise is considered and surface EMG sensors are used for quantifying the activity of the selected muscles. Different postures have also been evaluated during various exercises, such as standing vs. sitting [10,16]. Another group of studies compared the efficiency of exercises using the FLEXI-BAR with other types of exercises such as dumbbell or Sham-bar exercises [19,20,22].

Based on a thorough literature review, all studies that have thus far investigated the FLEXI-BAR are experimentally-based. To the authors' best knowledge, there are no existing models/simulation models in literature that can be used to predict and simulate the behaviour of the bar in alignment with musculoskeletal modeling software. In particular, the use of biomechanical models in conjunction with computer simulations is invaluable to investigate different musculoskeletal parameters, such as muscle forces and joint loads during different tasks [23–28]. Computer models are advantageous as they provide time and cost effective, modular means for investigating different exercises and exercise assistive devices with minimal or no experimental testing. Once properly validated, they also provide a convenient test bed for a wide range of 'What if" types of questions without subjecting an individual or patient to unnecessary testing. Therefore, the main objectives of this study are to first develop and validate an adequate computational model for the FLEXI-BAR, and secondly to implement the model in AnyBody Musculoskeletal modeling software to provide rehabilitation and sports specialists with an appropriate quantitative means for evaluating intervertebral disc and muscle forces during any type of exercise.

2. Methods

2.1. Modeling of FLEXI-BAR

In order to successfully model the FLEXI-BAR® Standard, different experiments were designed and conducted in order to establish the various parameters of the model as follows:

2.1.1. Experiments

Two different types of experiments were performed to evaluate the dynamic behavior of the system under different boundary conditions; i.e., free and forced vibration. A digital camera with 100-Hz data collection frequency was used for the first experimental test in order to observe the oscillation of the markers on the bar in a free vibration setting, where the grip part of the FLEXI-BAR was fixed (Fig 1A). The test was repeated three times using three different initial displacements, 5, 10, and 15 cm, respectively, at the end of the bar.

The second experimental test involved investigating the response of the bar under the condition of forced vibration. The grip was vibrated using a shaker and two inertial sensors (Xsense®, NL) were employed for measuring the acceleration of the grip and endpoint during the movement. The sensors were placed on the grip, as well as the endpoint of the bar (Fig 1B). The shaker was used

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