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A bio-inspired modular hierarchical structure to plan the sit-to-stand transfer under varying environmental conditions

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ABSTRACT

Human motion planning studies are of considerable importance in producing human-like trajectories for various industrial or clinical applications (e.g. assistive robots). In this case, the capability of Central Nervous System (CNS) in generating a large repertoire of actions can be inspirational to develop more efficient motion planning approaches. Here, inspired by structural and functional modularity in the CNS, a novel modular and hierarchical model is developed to plan the sit-to-stand (STS) transfer under varying environmental conditions. In this model, the planning process is distributed among several functionally simple modules. The cooperation of modules enables the model to plan the motion under a variety of conditions. The proposed model is assessed by planning the STS transfer under two types of environmental conditions: varying seat heights and varying base of support areas. The results revealed a suitable fit between the planned trajectories and the experimental trajectories for different conditions. It is demonstrated that a modular motion planner provides a higher accuracy and flexibility for the model to extend the planning process to various new conditions, yet still requires less computational complexity when compared with previous approaches. The proposed model is also supported by several behavioral and neurophysiological evidences.

1. Introduction

Mathematical modeling of human movement provides aiding tools to investigate various hypotheses on human motion planning strategies both from neurophysiological [1–3] and behavioral [4,5] standpoints. The studies on human motion simulation have assisted engineering evaluations to develop ergonomic and workplace interventions needed to accommodate individuals with prior disability [6]. In general, studies on human movement planning features can be divided into two groups. In the first group, there are optimization based models in which the optimization techniques are employed to assess human like trajectories. The major aim of optimization based models is to find suitable objective functions in order to generate the optimal trajectories of human body for a given task. Models such as minimum jerk [1], minimum torque change [7], and minimum variance [3] are among the common approaches in this category frequently used in different studies. Many studies in this group are focused on arm movements [1,2,5,8,9], however, there are also studies dealing with more complex tasks such as manual lifting [10], trunk bending [6], postural coordination [4], or gymnastics [11]. In general, the optimization based methodologies provided helpful insights about the optimal features of human movement, although, they suffered from several limitations as they could not justify the ability of the central nervous system (CNS) to apply previous experiences when facing new situations during motion planning process.

Recently, another group of motion planning approaches, known as data-based models, have been developed with the ability to derive simulated motions from real captured data [12–14]. The primary studies in this category were based on data storing strategy in which a database of empirical trajectories were constructed for a specific task, and the desired motion was extracted from the database for a given condition [12,13,15]. In further studies, the need to store the data was eliminated by applying artificial neural networks to learn the recorded trajectories instead of storing them [16]. Artificial

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neural networks provided more flexibility for the data-based models to generate the motion trajectories for a wider range of situations. Following this approach, a fuzzy logic based motion planner was also proposed, in which the experimental trajectories were used to design a set of fuzzy rules for a fuzzy controller to generate a task under different conditions [17]. In general, the data-based models were mainly focused on providing digital human models for industrial and ergonomic purposes (e.g. vehicle and workplace design) regardless of how they can interpret the neural control process in the CNS when planning a task [16–18]. In fact, the computational approaches used in data-based models were not necessarily bio-inspired, and they could not help to understand the motion planning mechanisms in the CNS [18]. The importance of bio-inspired motion planning models is derived from the fact that getting inspiration from the function of CNS in movement planning not only provides a better understanding of the CNS itself [19], but also enables the researchers to solve the consistency problem in human–robot interactions when using rehabilitative and assistive robots [20].

According to the above mentioned issues, the objectives of this work are presented as follows. First, inspired by several neurophysiological findings, this study aims to develop a mathematical interpretation of strategies that might be employed by the CNS when planning a task under different conditions. In this direction, two important hypotheses are considered; the motion decomposition hypothesis [21] and the functional/structural modularity of the CNS [22,23]. Inspired by the motion decomposition hypothesis [21], we suggest that if a complex task is decomposed into simpler sub-tasks (motion phases), the motion planning process would be simplified. Furthermore, according to previous findings about the existence of modular organizations in the CNS [23], we propose a novel modular and hierarchical motion planner (MHMP) with the ability to generalize the planning of a task to different environmental conditions.

As a secondary purpose, in this work we have chosen the task of sit-to-stand (STS) as our case of study to evaluate our proposed model. Previous approaches in human motion planning studies mostly dealt with manual lifting [13,16,17] and arm reaching tasks [1,2,8,9], due to their significance in industrial environments and motor control studies. However, one can hardly find studies dealing with STS transfer from the perspective of motion planning methods. STS is a frequently performed task among our daily activities, and is an important prerequisite for acquisition of functional abilities [24]. Clinically, STS is considered as a critical task to study patients with different movement disabilities, such as Parkinson's disease [25], or cerebral palsy [24]. In this case, studying STS movement through mathematical models can provide engineering and clinical insights for various applications associated with this task, such as functional electrical stimulation of patients with spinal cord injury [26]. The STS motion can be influenced by several environmental factors, such as, seat height, foot base of support area, foot position or arm position [27]. However, among all mentioned factors, the variation of seat height and base of support area highly affect the kinematics and the stability of motion, and thus, they are of major interest among researchers of clinical biomechanics [27–30]. Accordingly, in this paper, we consider the trajectory planning of STS transfer under the variation of seat height and base of support area as two influential environmental conditions.

In the following sections, we first give a brief explanation about the concept of motion decomposition in Section 2, and then introduce different parts of the proposed motion planning structure in Section 3. In Section 4, we explain the experimental study conducted to validate the model performance. In Sections 5 and 6 we present the results and discuss them from mathematical, structural and neurophysiological standpoints. Finally, in section 7, the major points of this study are summarized and the conclusions are drawn.

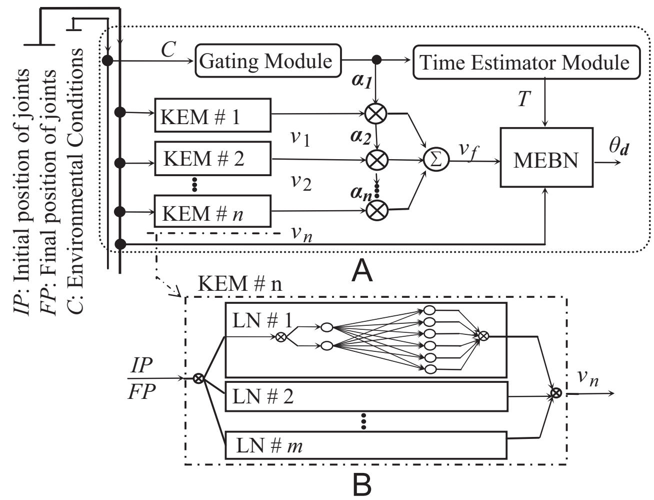

Fig. 1. (A) The structure of MHMP. The model contains several KEMs which estimate the joint angle values at via-nodes (v_i) under different conditions. A gating module determines the responsibility of each KEM over a given condition by allocating some gating coefficients (α) to each one. The movement element based network (MEBN) reconstructs the joint trajectories using the final estimated joint angle values (v_f) and the required time to plan the motion (T: estimated by time estimator module). (B) Each KEM contains several linear networks (LNs), each one responsible for estimating the angular values of one joint.

2. Motion decomposition

When studying human movement planning strategies, it is assumed that any complex motion is decomposed into several successive motion phases, each of which requires its own strategy to be performed [21]. It is assumed that the motion phases in a complex task are distinguished based on several biomechanical events (we call them nodes) during the movement. For a task with p phases of motion for example, there are p+1 nodes during the task; the initial node, the final node, and p−1 via nodes. In this work, the proposed model is developed based on the notion that a complex task can be identified only by the joint angle values at its discriminant nodes. Therefore, the trajectory planning process is reduced to estimate the joint angle values (including angular position, velocity and acceleration) of a limited number of nodes during the task, rather than the whole motion.

3. The structure of modular hierarchical movement planning (MHMP)

The proposed structure consists of four functional parts (modules) which can be categorized into two main levels (Fig. 1A). In the lower level, several kinematics estimator modules (KEMs) are responsible for the estimation of joint angle values of the motor system at via-nodes (i.e. angular position, velocity and acceleration). Also, a movement element based network at this level is responsible for the reconstruction of joint trajectories and preparing the final desired motion. In the higher level, a time estimator module determines the appropriate time duration for the task. There is also a gating module which coordinates the activity of KEMs to provide the best estimation of joint angle values under different environmental conditions. Gating module also contributes to calculate the time duration of movement.

The joint angular positions of the initial and final nodes (*IP* and *FP*) together with an index of environmental condition (*C*) are