Real-Time Closed-Loop Control of Human Heart Rate and Blood Pressure

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***Abstract*—Prolonged bed rest has significant negative impacts on the human body, particularly on the cardiovascular system. To overcome adverse effects and enhance functional recovery in bedridden patients, the goal is to mobilize patients as early as possible while controlling and stabilizing their cardiovascular system. In this paper, we used a robotic tilt table that allows early mobilization by modulating body inclination and automated leg movement to control the cardiovascular variables heart rate (HR) or systolic or diastolic blood pressures (sBP, dBP). The design and use of a control system is often done with a simulation model of a plant, but the time-variant and nonlinear nature of the cardiovascular system and subject-specific responses to external stimuli makes the modeling and identification challenging. Instead, we implemented an intelligent self-learning fuzzy controller that does not need any prior knowledge about the plant. The controller modulates the body inclination in order to adjust the cardiovascular parameters, with leg movement considered as a perturbing factor to the controller. The controller performance was evaluated in six healthy subjects. Measured mean values of HR, sBP, and dBP differed from desired reference values by 1.11 beats/min, 5.10 mmHg, and 2.69 mmHg, respectively. With this new control strategy, HR and dBP could be successfully controlled within medically tolerable ranges (deviations <2.5 beats/min and <5 mmHg from desired values, respectively). The control of sBP was less accurate; the results suggest that simultaneous control of multiple input stimuli rather than only adaptive automatic change of the tilt table angle might improve the controllability.**

***Index Terms*—Actuated tilt table, bed rest, cardiovascular system, early mobilization, fuzzy control, rehabilitation, reinforcement learning.**

I. Introduction

PATIENTS who require intensive care treatment, e.g., after stroke, are facing prolonged bed rest. Long-term bed rest negatively affects the cardiovascular, respiratory, musculoskeletal, and neuropsychological systems of these patients and can postpone recovery [1]–[3]. Early mobilization has the potential to promote functional outcome and accelerate recovery in these critically ill patients [4]–[6]. To mobilize the patients safely, their cardiovascular parameters have to be considered carefully. Control of these parameters is important to enable early mobilization while avoiding any further adverse effects e.g., decompensation due to fatigue or falling during mobilization [7], [8].

Here, our objective is to design an intelligent rehabilitation bed that allows automatic mobilization of bedridden patients while controlling and stabilizing their cardiovascular system. This will allow patients to get in a vertical position (stand and walk) while reducing risks of side effects, such as dizziness or syncope. It is expected that such a rehabilitation approach reduces secondary complications, personnel effort, and patient time in bed. As an initial prototype, we use a robotic tilt table that allows early mobilization through modulating body inclination and automated leg movement. These external mechanical stimuli are used in a closed-loop framework not only to provide early mobilization but also to control cardiovascular parameters, i.e., Heart rate (HR) and blood pressure (BP).

In our previous work, a nonlinear multiinput multioutput (MIMO) model predictive controller was developed to control HR and BP, and its feasibility was proven in patients [9]. The strategy was based on a relatively complex physiological model, required an identification phase of 11 min and presumed constant circumstances (e.g., no changes in hemodynamic response, which might happen due to different sources like alterations in blood volume over time [10]). Due to dependence of the controller on individual steady-state responses identified during the identification phase at the beginning of each session, changes in these assumptions over time could lead to deviations of the controlled values during the therapy session. The small differences between the nominal model used in the control and true system could be addressed by using robust control approaches. However, this might be of special concern in patients with autonomic nervous system dysfunction and continuous and significant changes in the cardiovascular response over time. Furthermore, the physiological model used in the previous strategy was constructed based on healthy subjects' body responses and there might be cases where the model does not fit due to underlying disease and a successful control experiment would not be possible.

In this paper, we move away from model predictive control toward model-free approaches [11], [12] that require neither an identification phase nor prior detailed knowledge about the human body. These characteristics allow adaptation of the controller to time-variant significant changes in the human body response regardless of physical characteristics (e.g., weight, height, lesion, etc. of the subject). As an initial step, we

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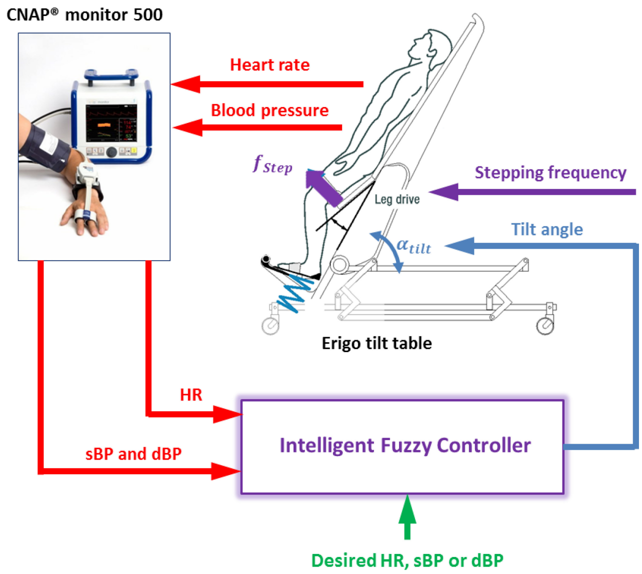

Fig. 1. Evaluation of the controller with tilt angle as input, HR, sBP or dBP as output, and stepping as disturbing factor.

TABLE I
PARTICIPATED SUBJECTS' DATA

Subject	Gender	Age	Weight[kg]	Height [cm]	BMI[a]
A	Female	24	70	178	22.1
B	Male	26	76	183	22.7
C	Male	28	108	168	38.3
D	Male	29	83	190	23.0
E	Male	29	85	192	23.1
F	Male	30	77.5	182	23.4

[a]BMI

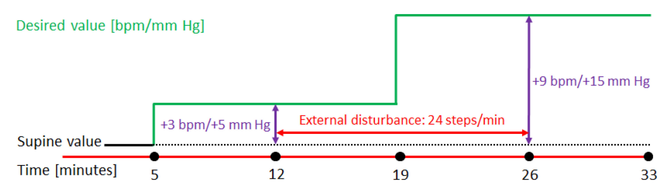

Fig. 2. Experimental protocol.

implemented an online self-adaptive fuzzy controller with a single-input single-output (SISO) structure. HR, systolic blood pressure (sBP) or diastolic blood pressure (dBP) values were controlled at desired values via the mechanical stimulus "body tilting." The controller learns from the interaction with the human subject. The goals of the present study were 1) to evaluate the controller performance in controlling the cardiovascular parameters among healthy subjects (with the inclination angle of the tilt table as only control input), and 2) to investigate the robustness of the controller with respect to significant external changes in the cardiovascular system response. To simulate such significant changes, we used passive stepping through the stepping device that is integrated in the Erigo tilt table (in an open-loop manner) as an external disturbance. The controller had no knowledge about utilizing this passive leg movement on the body and treated it as a disturbing factor (see Fig. 1).

II. Materials and Methods

A. Robotic Tilt Table and Measurement Equipment

The rehabilitation tilt table Erigo (Hocoma AG, Volketswil, Switzerland) is a robotic tilt table enhanced with a motor-driven stepping device. The inclination angle α of the table can be continuously adapted between 0° and 75°. Passive leg movement is provided by two leg drives with a constant adjustable speed between 0 and 80 steps/min (maximum stepping frequency of $f_{\max.\ \mathrm{Step}} = 1.33$ Hz) and equal periods of extension and flexion phases (see Fig. 1).

For the continuous noninvasive measurement of biosignals (i.e., HR and BP), a CNAP monitor 500 (CNSystems AG, Austria) was deployed. The monitor requires a short initial calibration for each subject (about 2 min), and uses an arm and a finger cuff to measure the BP signal. The raw BP signal was extracted from the monitor in terms of an analog signal with the rate of 100 Hz and via a galvanic separation (for safety reasons) fed into an input card of the bed PC. The BP wave signal was buffered online. The peaks of the signal were detected and averaged, allowing real-time values of sBP and dBP to be computed. Moreover, heart period was obtained by averaging the time length between successive dBP peaks in order to calculate the real-time HR value.

B. Subjects and Experiments Protocol

The controller was evaluated in six healthy subjects (age ± standard deviation (SD)): 27.7 ± 2.05 years; height: 182.2 ± 7.9 cm; weight 83.2 ± 12.1 kg; body mass index (BMI) 25.4 ± 5.3). The participants had no known cardiovascular disease (for further details, see Table I). Informed consent was obtained from all subjects.

For each subject, three experiments of HR, sBP, and dBP control were done. Each experiment took 33 min. Since a stabilized steady-state response of the cardiovascular system at a sustained position can be reached in about 5 min [13], each experiment started with a 5 min initial measurement in the supine position, followed by four 7-min blocks where the controller had to keep the HR or each BP signal at predefined values by providing the appropriate inclination angle. To evaluate the performance of the controller and detect potential limitations of the system, appropriate, predefined desired values had to be chosen. To calculate the appropriate desired values and to obtain an approximate value for the steady-state response, the cardiovascular parameter was averaged during the last minute of the initial 5 min supine position phase. Then, we assigned the set points: For the HR control experiment, 3 beats/min for the first two 7-min blocks, and 9 beats/min for the second two blocks, were added to the calculated steady-state supine values (see Fig. 2). For BP experiments, 5 and 15 mmHg, respectively, were added to the calculated steady-state supine values. The goal from choosing relatively lower set point values in the first two 7-min blocks was to evaluate the performance of the controller and its robustness with respect to external disturbance. For the second two blocks, higher values were assigned to find potential limitations of the

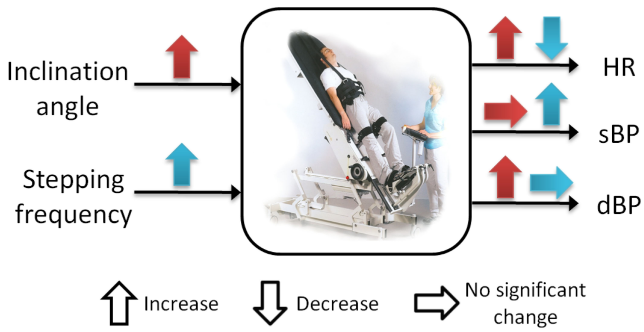

Fig. 3. General steady-state response of cardiovascular parameters to passive tilting and stepping.

system. To evaluate the performance of the controller with respect to external disturbance, a passive leg movement (stepping) with a constant frequency of 24 steps/min was initiated in the beginning of the second 7-min block and continued for 14 min (to cover the third block as well, see Fig. 2).

C. Cardiovascular System Response of Healthy Subjects

In general, passive tilting results in an increase of the HR and the dBP [13]–[21] in healthy subjects, while the sBP either increases [13], [14] or does not change [15]–[21]. Similar changes can be observed in patients [22]–[24]. Even in healthy subjects, passive tilting can result in syncope [25], which can be prevented through additive passive leg movement [25], [26]. As the inclination angle during passive tilting has an either increasing or stabilizing but not decreasing effect on the cardiovascular parameters, we assume a positive monotonicity with increasing inclination angle.

To our knowledge, there are no consistent quantitative data on the effect of passive leg movement alone on the cardiovascular system. In our previous work, we observed that passive stepping induces 1) an initial increase in the HR followed by a decrease, 2) increase in sBP, and 3) no significant effect on dBP [9] (see Fig. 3).

D. Self-Adapting Fuzzy Controller Design

Generally, design of a control system requires a model of the plant in order to meet desired performance objectives. However, a physiologically realistic model of the cardiovascular system is difficult to obtain due to factors such as nonlinearity, intersubject, and time variability. As an alternative approach, we propose a self-adaptive fuzzy controller that does not need any previous knowledge about the plant. The controller is a zero-order Takagi–Sugeno type fuzzy controller [27] enhanced with self-adaptive capability, which combines the fuzzy logic control with reinforcement learning concepts [12]. Error (*E*) and change in error (*CE*) between measured and desired biosignal values (i.e., HR, sBP, or dBP) were considered as inputs to the controller. The structure of our controller was defined using the three membership functions (MFs) "negative," "zero," and "positive" for each variable, *E* and *CE* (see Fig. 4). The three MFs divide the range of *E* and *CE* into three different areas of

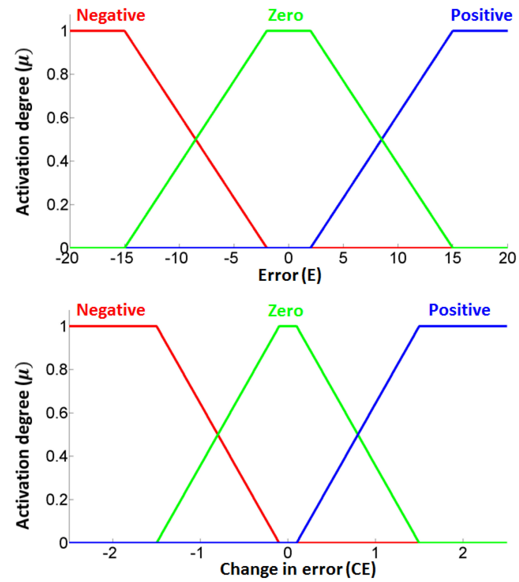

Fig. 4. Fuzzy controller structure used in this study; E = Error and CE = Change in error, MFs represented in colors.

negative, zero (negligible value), and positive. Hence, the controller is composed of nine rules with scalar value consequences. In the proposed fuzzy controller, multiplication is used as T-norm operator to compute the firing strength of each rule and weighted average is used for "defuzzification." Thus, the controller output at time step *k* is

$$\alpha_{\text{inclination}} = \frac{\sum_{i=1}^{n} C_i f_i}{\sum_{i=1}^{n} f_i} \tag{1}$$

where *n* is the total number of rules (all possible combination of MFs of *E* and *CE* without repetition), which is here "nine." C_i is the consequence of the *i*th rule, and f_i is the firing strength of each rule, which can be calculated using

$$f_i = \prod_{j=1}^{T} \mu_j \tag{2}$$

with *T* as the number of MFs associated with each rule (number of input variables, i.e., here $T = 2$), and μ_i as the activation degree of MFs associated with the corresponding *i*th rule.

At the start of each experiment, the rule consequences are initialized at zero and adapted during the experiment by interaction with the plant (i.e., the human body, based on the strategy employed from [12]). At each step, the rule consequences are adapted online based on the error between the output of the plant (y_k = measured HR, sBP, or dBP at time *k*) and the previously attempted desired value, r_{k-1}. The error $e_k = r_{k-1} - y_k$ is considered at every time step and a correction (reward/punishment) is applied on the rule consequences that have been responsible for the error. Assuming a positive monotonicity of HR, sBP, and dBP responses (see Section III), three conditions can be considered for the reward or punishment of rule consequences:

1) A negative error $y_k > r_{k-1}$ implies that the previously applied inclination angle at time *k* has been too large and

the consequences of the involved rules should be punished (decreased).

2) A positive error $y_k < r_{k-1}$ implies that the previously applied inclination angle at time *k* has been too small and the consequences of the involved rules need to be rewarded (increased).
3) Reaching the desired value $e_k = 0$ demonstrates that the previously applied inclination angle at time *k* has been sufficient and no change in rule consequences are needed. Since the contribution of each rule to the current error is different, the reward/punishment for each rule has to be proportional to the degree of contribution (i.e., the firing strength of each rule at the previous time step). Therefore, the *i*th rule consequence will be rewarded/penalized, (i.e., increased/decreased) based on the following formula:

$$\Delta \mathrm{C}_i(k) = L.f_i(k-1).e(k) \tag{3}$$

with "*L*" as the learning factor of the controller, which is known from prior knowledge about the plant. Its absolute value is defined as

$$|L| = \frac{\Delta u}{\Delta r} \tag{4}$$

where Δu is the range of change in the input variable (*inclination angle* α) and Δr is the range of possible changes in the output (HR, sBP, or dBP) caused by the input. The inclination angle of the bed varies between 0° and 75° ($\Delta u = 75$). Based on available experimental data, it was assumed that the maximum change in response due to inclination angle would be about 60 (beats/min or mmHg) such that ($\Delta r = 60$) was chosen. Accordingly, during our experiments, a constant learning factor of $L = 75/60 = 1.25$ was used. The rule consequences are updated in an online manner using

$$\mathrm{C}_i(k) = \mathrm{C}_i(k-1) + \Delta \mathrm{C}_i(k). \tag{5}$$

The direction of the change ($\Delta \mathrm{C}_i(k)$), i.e., increase/decrease of rule consequence is determined by the sign of *e(k)*, for which each rule consequence has to be applied. If the plant response (e.g., HR) with respect to the control input (*inclination angle* α) has a negative monotonicity, then the applied change has to be in the opposite direction and consequently a negative sign has to be added to (3).

To compensate physiological dead time and transient phases in the natural response of the cardiovascular system to a change in the inclination angle, the sampling time of the controller was set to 20 s and the control input was applied every 20 s.

E. Filtering of the Signals

The goal was to control the long-term dynamics of the cardiovascular parameters. To cut the frequencies not representing the long-term dynamics, low-pass filtering of the biosignals was necessary. These frequencies not only include high frequencies such as measurement noise, but also low frequency, natural physiological fluctuations [28]. Before entering the control loop, HR, sBP, and dBP biosignals were filtered using a moving average infinite impulse response filter of the Direct-Form II [29],

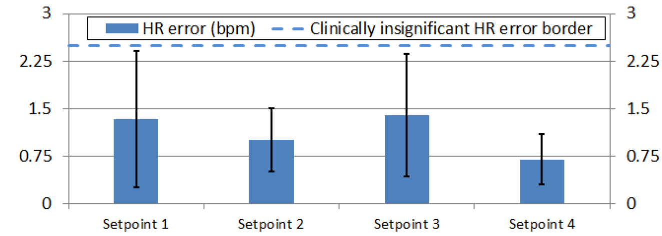

Fig. 5. Mean absolute errors of HR (columns) and corresponding SDs (black lines) among six healthy subjects. Set points 1 and 2 correspond to addition of 3 beats/min, and set points 3 and 4 to addition of 9 beats/min to the steady-state supine value. The stepping was active during set points 2 and 3.

which attenuates noise but also the short-term natural fluctuations. For the HR, a window size of 30 (group delay of 14.5 s) and for the BP signals, a window size of 10 (group delay of 4.5 s) with a sampling frequency of 1 Hz were used. These values correspond to cutoff frequencies at approximately 0.02 and 0.04 Hz, respectively, and attenuation of around 30% of the signals at these frequencies.

F. Performance Evaluation of the Controller

The difference between the true, nonfiltered measured biosignals and the desired values during the last 2 min of each of the four 7-min experimental phases was computed. The mean and SD of the errors of each experimental phase were calculated for all subjects (see appendix). We considered that mean values stand in for long-term dynamics of the cardiovascular system, while SDs represent natural short-term fluctuations. Based on the literature [30]–[32] and personal communications with physicians, deviations of less than 2.5 beats/min for HR and 5 mmHg for both sBP and dBP are clinically insignificant and, thus, can be considered as successful control of desired values.

III. Results

The average of absolute mean error for HR over all the four set points was below 2 beats/min for each subject (see Fig. 5). The total absolute mean error was greater for sBP compared to dBP, whereas the error SDs (i.e., short-term dynamics) did not differ significantly. We calculated the average of absolute mean errors in HR and BP, and their corresponding SDs among the subjects (see Figs. 5 and 6, respectively). Fig. 7 depicts the controller performance in one of the subjects where the filtered value shows how successful the controller was in reaching the desired values.

In the first two 7-min blocks, the set points were chosen to show the performance of the controller and its robustness with respect to external disturbances. During these set points for HR, sBP, and dBP, an average absolute error of 1.17 beats/min, 2.44 mmHg, and 0.85 mmHg were observed, respectively. Considering performance evaluation in all the four blocks, average absolute errors for HR, sBP, and dBP were 1.11 beats/min, 5.1 mmHg, and 2.69 mmHg, respectively.

In the present study, the first two set points were chosen such that they show the accuracy and robustness of the proposed controller, and the second two set points were chosen to show

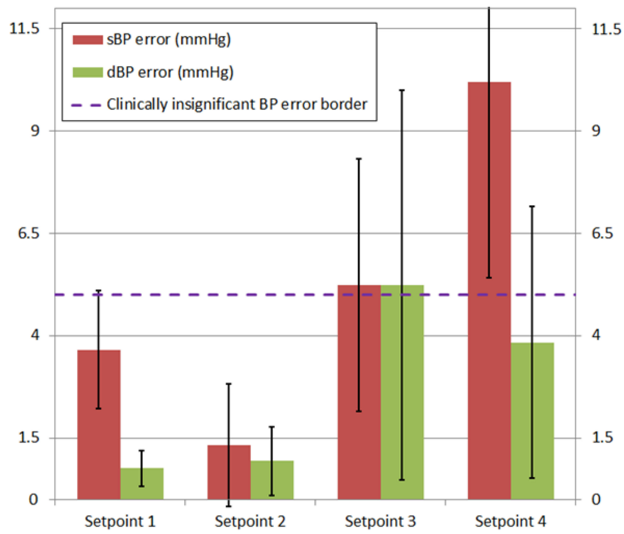

Fig. 6. Mean absolute errors of sBP and dBP (solid columns) and corresponding SDs (black lines) among six healthy subjects. Set points 1 and 2 correspond to addition of 5 mmHg, and set points 3 and 4 to addition of 15 mmHg to the steady-state supine value. The stepping was active during set points 2 and 3.

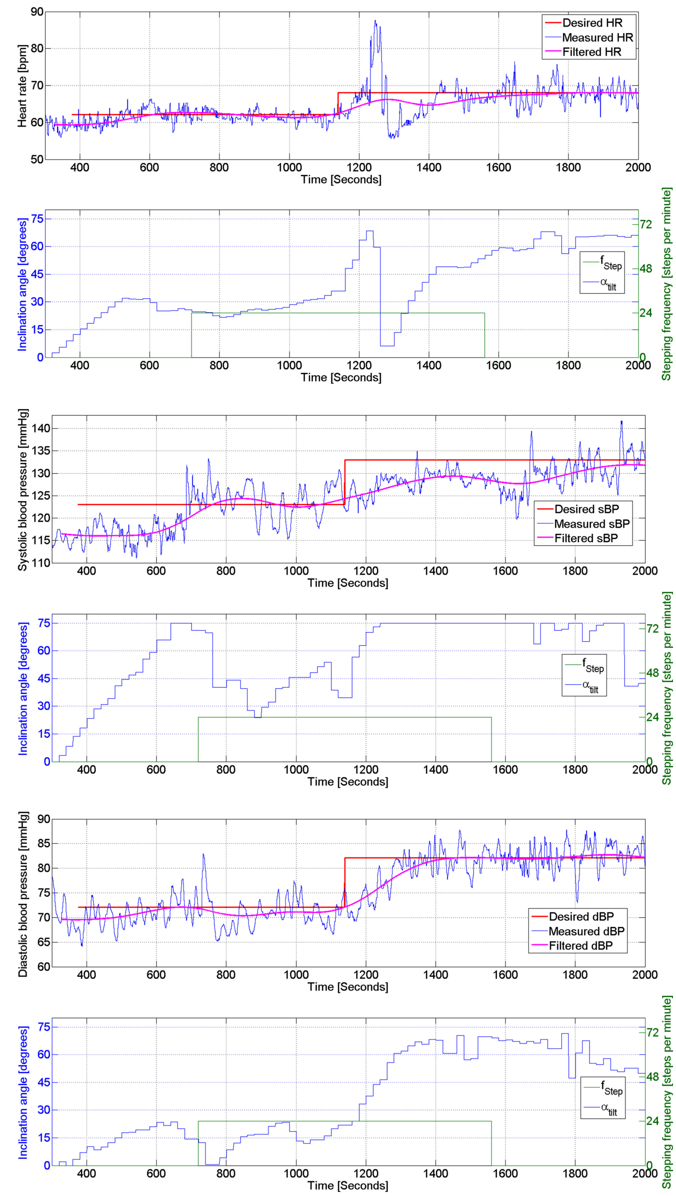

Fig. 7. Evaluation of the controller on subject E; SISO control of HR, sBP, and dBP through inclination. To illustrate the biosignal trend, the measured signal was zero-phase filtered [1] by a second-order Butterworth filter with a cutoff frequency of 0.02 Hz.

the limitations of the system and borders of the reachable values when trying to affect cardiovascular parameters through applied external stimuli. Hence, the control of variables generally seems to be more difficult in the last two set points. HR could be controlled accurately in all the four set points, and the errors were generally below 2.5 beats/min (i.e., clinically insignificant error border). dBP could be controlled accurately only during the first two set points, and the errors during these two set points were generally below 5 mmHg (clinically insignificant error border). In contrast to dBP, the sBP could hardly be elevated to 5 mmHg with tilting alone (without stepping). Successful control was only observed in the second 7-min block with an average absolute error of 1.32 mmHg, and an increase of +5 mmHg with respect to the supine value when stepping was added. The comparison of "set point 1 and set point 2 together," and "set point 3 and set point 4 together" reveals that the controller reaches the desired values of sBP only when the stepper is active.

While passive tilting might result to syncope [25], no such occasion was observed during the study.

IV. Discussion

Previous efforts to control cardiovascular parameters nonpharmacologically have been mainly focused on control of the HR with the aim to increase motivation of users during exercise games [33] to provide optimum exercise protocol in sport training or rehabilitation [34], [35], or to increase patient engagement without undue harm during the rehabilitation process [36], [37]. The primary focus has been on HR control during gait training and various control strategies have been proposed. HR control was achieved through adjustment of gait speed either voluntarily [37] or by automated adaptation of treadmill speed [34], [37]–[39]. The proposed strategies require either an identification phase of a relatively complex model or tuning of the parameters in preexperiments. Apparently, they are only applicable to healthy subjects or patients who are able to walk. There has been almost no attention on nonpharmacological control of cardiovascular parameters in bedridden patients. In this paper, we addressed the control of cardiovascular parameters in bedridden patients to rehabilitate their deconditioned cardiovascular system following the long duration bed rest. The proposed self-adapting fuzzy controller enabled us to control cardiovascular parameters of the subjects independent of the characteristics of the single subjects enrolled in the study.

A. Controller Performance

In general, dBP control was more successful than sBP control. This result is in agreement with other studies [15]–[21]

that report hardly distinguishable changes in sBP as a reaction to passive tilting, indicating rather physiological features of healthy response to tilting than technical limitations. HR, in contrast, could be controlled accurately in all conditions and even increased to 9 beats/min in the last two set points.

The study design with the stepping disturbance only active in set points 2 and 3 was unsymmetrical. However, due to adaptation of the controller to the external disturbance in set points 2 and 3, the withdrawal of stepping in set point 4 can also be considered as another disturbance to the controller. Nevertheless, as the HR results suggest, the controller successfully adapts and copes this challenge. Such a conclusion is more difficult to make in case of sBP and dBP, as during the last two set points, in most cases, the set points are unreachable and the control input goes to saturation.

The rise time is another important aspect of the controller performance. In the initial learning phase when the controller is relatively naive, the rise time of the controller depends on the speed of learning (i.e., learning factor “L”), and furthermore, it depends on how steep each individual’s body reacts to tilting. After the initial learning phase, the reaction is expected to be faster; however, it might be constrained by the speed of the actuators (a full tilt from 0° to 75° takes approximately 20 s). Since the cardiovascular system response is nonlinear with respect to tilting and is subject dependent [15], and moreover, the study design is unsymmetrical and the controller continuously learns, the exact analysis of the controller rise time is difficult to make. However, as the analysis of controller performance in reaching the desired value is performed in the last 2-min periods of each set point, the results suggest that on average a 5-min time period is enough to learn the body reactions and reach the desired values. Considering the clinical settings such as intensive care (24 hr patient support) or short-term therapy (30–60 min duration), the mentioned time period (about 5 min) seems to be acceptable. One point which might arise here is whether the difficulty in control of sBP might be also due to the learning process and rise time of the controller. The observations suggest that in case of sBP, the issue is rather lack of reaction with respect to inclination angle, as in many cases, one can observe saturation in the control input without reaching the desired value (e.g., sBP response of subject E in Fig. 7 at around 650 s).

The order of the set points is another important issue to be considered when interpreting the results. While introduction and withdrawal of stepping can be considered as a disturbing factor to the controller and, therefore, imposes adaptation of the controller, the longer learning time, and therefore, the opportunity to learn from more actions is expected to improve the controller performance. Therefore, beside all the issues, to some extent, it can be expected that the controller in set point 4 performs better than, for example, set points 1 or 2. This means that, for example, when the lower set points 1 and 2 are skipped and we directly start with the higher set point (i.e., set points 3 and 4), the controller needs to explore a larger space (go to higher angles), and therefore, the initial rise time is expected to be larger. However, when the initial learning phase is passed, no significant changes in controller performance (e.g., rise time) are expected by reordering the set points.

Besides stepping and tilting, other factors, e.g., psychological factors, might influence the cardiovascular system. The influence of such factors could also be observed in the result of subject E (see Fig. 7), where, after the change of the set point at 1140 s (third 7-min block), a large peak in HR could be seen. It exemplifies the learning strategy of the controller. In the beginning, the controller tried to increase the HR by increasing the inclination angle but had no success in reaching the desired value. Later, in the sequence of increasing the inclination (occurring between 1140 and 1220 s), the controller experienced a sudden, unexpected HR increase at 1240 s and, consequently, strongly responded by decreasing the inclination angle. Eventually, the controller was successful to reject this unknown-source external disturbance and to regulate the HR to the desired value.

The main advantage of the controller is its ability for adaptation and response to external disturbances. However, positive monotonicity of the human body response with respect to tilting was considered for the control strategy in healthy subjects. In case of patients, reactions might be different due to the underlying disease (e.g., autonomic dysregulation) or medication [22]–[24]. As the next step, we should, therefore, check whether the assumption of positive monotonicity holds in a patient population. Nevertheless, the positive monotonicity assumption might hold in many settings (e.g., increase of HR by physical activity intensity), which make the proposed controller potentially applicable to other domains outside the scope of our paper (e.g., gait training).

The adaptability of the controller allowed us to select our subjects without considering their physical characteristics such as height and weight. As an example, subject C shows a relatively large BMI factor which sets him apart from other subjects. However, the controller performance on this subject was similar to other subjects; successful HR control in all conditions, sBP control in set point 2, and dBP control in set points 1 and 2. Nonetheless, similar to any other adaptive control scheme, in our approach, the persistency of excitation and convergence of the controller parameters to true values is a challenging topic and requires further investigations [40].

B. Pathophysiological Considerations

We propose that early mobilization under control of the cardiovascular parameters may be capable to effectively restore cardiovascular conditioning in bedridden patients. Autonomic dysregulation has been recognized as an important factor of cardiovascular deconditioning. Altered cardiovascular reflex responses [41] with decrease in the cardiac baroreflex sensitivity and alteration of the sympathetic–parasympathetic balance [42] play major roles for the onset of orthostatic intolerance after prolonged bed rest [43]–[45]. A decrease in BP can be partially compensated by the body through a rise in HR. But a sudden deflection in the BP in absence of further HR increases precedes orthostatic hypotension [43]. Control of the cardiovascular parameters with early recognition of threatening values during early mobilization may not only allow to retrain the reflex responses by exercising within safe limits but also to restore functional capacity to before-bed rest levels.

TABLE II
CONTROLLER PERFORMANCE ON HEALTHY SUBJECTS (μ IS THE MEAN ERROR AND σ THE SD)

Experiment	Subject	Set point 1		Set point 2 (Set point 1 + f_{step})		Set point 3 (Set point 4 + f_{step})		Set point 4		Total (absolute mean)	
		μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
HR (beats per minute)	A	–0.74	2.25	0.73	4.96	–1.21	3.13	–0.33	2.3	0.75	3.16
	B	3.66	4.27	–1.3	1.52	–1.76	4.35	–1.14	3.13	1.96	3.32
	C	1.21	1.93	0.2	2.06	–0.59	2.58	0.94	2.88	0.73	2.36
	D	1.28	1.96	–1.85	2.82	–3.34	3.76	0.94	3.19	1.85	2.93
	E	0.58	1.92	–1.01	1.3	–0.93	1.87	0.01	2.03	0.63	1.78
	F	0.56	2.78	–0.95	1.61	0.54	3.18	–0.83	3.28	0.72	2.71
sBP (mmHg)	A	2.94	3.14	–4.43	5.14	–6.91	4.29	–10.96	2.51	6.31	3.77
	B	–1.79	5.35	0.23	3.03	–4.07	2.69	–12.84	3.26	4.73	3.58
	C	–6.25	1.69	–1.31	3.34	–11.14	1.89	–11.54	2.44	7.56	2.34
	D	–3.02	4.07	0.28	2.92	–1.44	5.77	–16.42	2.42	5.29	3.79
	E	–3.2	4.61	1.57	3.36	–3.98	1.28	–0.92	3.52	2.42	3.19
	F	–4.72	3.33	0.11	1.48	–3.87	2.62	–8.51	2.01	4.30	2.36
dBP (mmHg)	A	–0.54	2.57	0.19	3.14	–6.39	2.0	–5.59	2.74	3.18	2.61
	B	0.37	1.67	–1.12	2.8	–14.5	2.01	–9.8	1.21	6.45	1.92
	C	–1.33	1.41	–0.02	2.7	–6.12	2.47	–4.93	3.58	3.1	2.54
	D	1.4	2.89	–2.23	2.98	0.85	4.86	–1.0	5.39	1.37	4.03
	E	0.49	2.48	–1.78	2.06	–0.27	2.57	0.68	2.13	0.8	2.31
	F	0.42	1.95	0.27	1.26	–3.22	1.30	–1.01	1.11	1.23	1.41
Total (absolute mean)	HR	1.34	2.52	1.01	2.38	1.40	3.15	0.70	2.80	1.11	2.71
	sBP	3.65	3.70	1.32	3.21	5.24	3.09	10.20	2.69	5.10	3.17
	dBP	0.76	2.16	0.94	2.49	5.23	2.54	3.84	2.69	2.69	2.47

f_{step} is applied stepping pattern considered as external disturbance.

The table shows the detailed performance of the controller on every subject and at each set point. μ is the mean error between measured and desired values during the last 2 min of each set point. σ is the SD of the error during the same period and represents the short-term dynamics of the cardiovascular parameter.

The main goals of the study were to present this novel rehabilitation approach and validate the proposed control strategy. To this end, we decided to choose exact and clinically significant values as set points. In clinical setting, however, the goal is to control and keep the cardiovascular parameters within a certain range (e.g., HR between 60 and 100 beats/min or sBP between 120 and 140 mmHg [46]). Extension from controlling exact values to intervals is a simplification of the current approach. By putting the set points in the middle of the clinically relevant desired ranges, the control loop would try to keep the cardiovascular parameters in the middle of the target intervals, and therefore, it would continuously maximize the distance from the unsafe borders.

C. Limitations

The main limitation of our approach to control the human body originated from existing constraints both in inputs (i.e., the range of applicable physical stimuli) and outputs (i.e., the range of achievable range of physiological outputs). As an example, the steady-state response of the cardiovascular system to tilting in average corresponds to 15–30% HR increase, 10–15% dBP increase, and no significant change in sBP [15].

A multiinput single-output structure instead of SISO would allow physiological signals such as sBP to be controlled more precisely and over a wider range, as multiple inputs (e.g., stepping, inclination) could be used to affect each output. However, it is questionable whether this could be implemented using the same method that we presented here as it would require us to be able to identify each input's exact contribution to the error. This might be complex when both inputs are changed simultaneously. To control multiple parameters simultaneously (e.g., HR and sBP together [9]), designing a MIMO control structure would be required.

V. CONCLUSION AND OUTLOOK

Early mobilization can avert negative effects of long bed rest and side effects may be prevented with control of the cardiovascular system. Control of cardiovascular parameters is governed by autonomic nervous system and, in particular, baroreflex regulation. Impairment of this internal controller causes orthostatic intolerance and is prevalent among bedridden patients. Due to the involved risks, this makes the patients mobilization cumbersome. Augmentation of the impaired internal controller by using an external controller providing suitable external stimuli type and intensity might impede associated risks such as sudden drop of sBP and consequence syncope during mobilization in patients. The goal of this project is to mobilize bedridden patients very early while controlling the cardiopulmonary function through external mechanical and electrical stimuli. As an initial step, this paper proposes an online self-adapting SISO fuzzy controller for HR, sBP, and dBP control through inclination and learning without detailed knowledge about the human body. The experimental results show successful results for HR and dBP control, while sBP could only be regulated within small ranges; adding stepping increased the reachable set of sBP. Therefore, additional external stimuli might be required to successfully control the cardiovascular system and keep the variables within safe ranges for patients. In a next step, we will integrate stepping and functional electrical stimulation of leg muscles as additional control inputs into a MIMO control structure, and study the outcome in bedridden patients over a prolonged time (several hours).

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APPENDIX

See appendix Table II in previous page.

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