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Citation for published version:

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Proceedings of the International Conference on Humanoid Robots (Humanoids 2018)

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Learning Whole-body Motor Skills for Humanoids

Chuanyu Yang, Kai Yuan, Wolfgang Merkt, Taku Komura, Sethu Vijayakumar, Zhibin Li

Abstract—This paper presents a hierarchical learning framework that can learn a wide range of push recovery and balancing behaviors, i.e., ankle, hip, foot tilting, and stepping strategies. The policy is trained in a realistic physics simulator using the robot model in a setup designed to be able to easily transfer and deploy synthesized control policies to real-world platforms. The advantage over traditional methods that integrate high-level planner and feedback control is that one single coherent policy network is generic for generating versatile, unprogrammed balancing and recovery motions against unknown perturbations at arbitrary locations (e.g., legs, torso). Furthermore, the proposed framework allows the policy to be learned with any state-of-the-art learning algorithm. By comparing the proposed approach with other methods in literature, we found the performance of learning is similar in terms of disturbance rejection with additional benefits of generating generic and versatile behaviors.

I. INTRODUCTION

Legged robots have great potential for being deployed in environments where wheeled robots are limited, such as obstacle obstructed terrain as well as narrow and elevated surfaces (e.g., stairs). However, in contrast to wheeled or tracked robots, humanoids are intrinsically unstable and require active control to balance due to their limited support area, high center of mass, and limited actuator capabilities. Therefore, the range of possible scenarios in which humanoids can be deployed is mostly limited by the humanoids’ ability to maintain balance and deal with disturbances and uncertainties. Balance can therefore be considered as one of the core skills for humanoid robots and locomotion.

Classical control methods propose a wide range of balance recovery algorithms, which however lack in the universality of their application. In order to deal with a wide range of pushes, different control strategies need to be applied and traditionally a switching between controllers for the given situation is needed. Generally, different sets of parameters are used for the four main push recovery strategies: ankle, hip, foot-tilting, and stepping (cf. Fig. 1).

Methods from machine learning on the other hand provide a promising alternative as they can incorporate multiple push recovery skills without the need for hand-tuned gains. Their use is motivated by three main factors:

First, supplementing existing control strategies with learning methods allows dealing with scenarios that are hard to engineer in a traditional sense such as sudden, high impact forces and discrete, sudden switches of contact.

Second, in contrast to planning and control algorithms that demand high computational power to run at or close to real-time, e.g., Model-Predictive Control, the computation for machine learning approaches can be outsourced offline [1]. I.e., the computation for Deep Reinforcement Learning (DRL) can be off-loaded into the neural network training phase. By doing so, faster online performance for high dimensional control systems such as humanoids can be achieved.

Last, in recent years, DRL has been shown to be capable of solving complex manipulation and locomotion tasks that involve learning a control policy in high-dimensional continuous observation and action spaces [2]–[4]. Instead of manually tuning the control parameters, a feasible policy is learned through interaction with the environment.

While there exist various studies using DRL to learn bipedal locomotion for humanoids [5]–[7], the used robot models leverage simplified dynamic and collision models and environments in order for faster than real-time simulations at the cost of less realistic simulations. The motivation of this paper is to learn locomotion skills using a realistic robot model obtained from system identification in a realistic simulation environment in order to apply the learned skills on the real robot. We leverage recent advances in DRL to design a unified balance recovery controller which is able to generate sequences of actions that perform similar to or even exceed traditional methods with respect to their disturbance rejection ability. Our work has the following contributions:

1) Application of DRL on an accurate robot model of the Valkyrie platform with realistic settings for simulation.
2) Design of a learning framework that generates a generic policy. This policy captures a variety of sensor-motor synergies and various control strategies emerge in a
unified manner without the need of multiple controllers and the related switching mechanism.
3) Proposal of a balance recovery specific reward design and training settings of disturbances. These allow the exploration of versatile motions and as a result human-like balancing behaviors, such as foot-tilting and stepping, emerge naturally.
4) Benchmarking the learned policy against control methods. The learned policies generate balance recovery strategies which reject impulses in a similar (or even superior) magnitude as traditionally designed controllers.

This paper is organized as follows. A brief review on conventional push recovery methods and DRL is presented in Section II. Background information on some concepts of DRL and push recovery is explained in Section III. The proposed methodology is elaborated in Section IV. The obtained results are demonstrated and discussed in Section V. Finally, a conclusion is drawn in Section VI.

II. RELATED WORK
A. Conventional Push Recovery methods
Over the past two decades, remarkable progress in the field of push recovery for humanoid robots has been made. Without the use of arms, humanoids can leverage four lower body balancing strategies: ankle, hip, stepping, and foot-tilting. The first three strategies, controlling ankle torque, angular momentum around the Center of Mass (CoM), and the timing and position of steps, are analyzed with respect to their ability to reject disturbances in [8]. A control framework for the foot-tilting strategy has been proposed in [9] demonstrating a humanoid’s ability to use foot-tilting for push recovery. Traditionally control schemes can be divided into predictive schemes which calculate reference motions, and reactive schemes which respond to sudden disturbances.

A Model Predictive Control (MPC) scheme that constrains the Center of Pressure to be within the Support Polygon has been proposed in [10]. Strategies involving modulating the Angular Momentum to reactively deal with disturbances have been formally analyzed in [11], [12]. Due to the limited size of the contact area, i.e. the foot size, stepping strategies have been proposed [13], [14]. This idea was formalized as the Capture Point (CP), the point on which one needs to step in order to come to a complete halt [11]. Enlarging the support area by stepping has been extended to multi-contact push recovery scenarios in [15], [16]. Methods for balancing on inclined slopes has also been proposed [17]. Lastly, strategies modulating the height of the CoM in order to compensate for disturbances have been proposed in [18]. This CoM height modulation can be achieved by either lengthening the leg or in form of foot tilting [9].

B. Deep Reinforcement Learning of Locomotion
There exists various successful studies using model-free DRL to solve bipedal locomotion tasks in 3D simulation environments. Schulman et al. proposed a DRL algorithm, Proximal Policy Optimization (PPO), which was applied to successfully learn a locomotion policy that is capable of heading towards a target location in the Roboschool humanoid simulation environment [4]. PPO, together with Deep Deterministic Policy Gradient (DDPG) [3] and Trust Region Policy Optimization (TRPO) [2], are the most commonly used state-of-the-art DRL algorithms for continuous observation-action space control. Further extensions include a parallel computing version of PPO, Distributed Proximal Policy Optimization (DPPO) [19], which was applied on a humanoid and successfully learned dynamic and diverse parkour movements for the humanoid character.

Various frameworks have been proposed to allow the DRL agent to learn a policy that generates human-like locomotion behavior for bipedal locomotion tasks. Merel et al. proposed a framework that uses generative adversarial imitation learning [20] to enable the network to learn a policy that produces human-like locomotion gait using limited demonstrations from motion capture data [21]. Peng et al. proposed a framework that incorporated imitation learning by reshaping the reward through the introduction of an imitation term that provides higher reward when the motion is closer to the reference motion capture data [22].

III. BACKGROUND
A. Software Setup
The simulation environment of the Valkyrie robot is built using PyBullet [23] (Fig. 2). The robot model used in the simulation is the NASA Valkyrie robot [24] with realistic inertia, center of mass, and joint actuation limits. Self-collisions are enabled in the simulation. The DRL algorithm is built using Tensorflow [25].

B. Deep Reinforcement Learning
For learning a suitable policy, Deep Reinforcement Learning, particularly model-free policy gradient methods, are
used. Policy gradient algorithms operate by maximizing the direct sum of rewards with reference to a stochastic policy. The policy gradient algorithms used in this work are the TRPO [2], PPO [4], and DDPG [3]. Due to resulting in the best and most robust policy, the TRPO algorithm will be outlined in the following.

1) Trust Region Policy Optimization: In practice, policy gradient methods suffer from high variance which can lead to fluctuations in the performance of the policy between iterations. This problem of instability during training is remedied by introducing a trust region to the numerical optimization which takes a step in the improving direction within a determined trust region. By constraining the amount of changes to the parameters, measured by the Kullback-Leibler (KL) divergence, TRPO guarantees a theoretical monotonic performance improvement of the reward.

For every parameter update iteration, TRPO performs several rollouts and stores the state $s_t$, action $a_t$, and reward $r_t$, into a batch $D$ until enough data samples are collected, which will then start the update process. During the update process, TRPO updates the policy parameters by minimizing a surrogate loss function while constraining the KL divergence between the new and old policies $\pi_\theta$, $\pi_{old}$ to remain within a trust region:

$$\min_\theta L_{old}(\theta) = -\mathbb{E}_t \left[ \pi_\theta(a_t|s_t) \left( \frac{\pi_{old}(a_t|s_t)}{\pi_\theta(a_t|s_t)} A_t \right) \right]$$

subject to $\mathbb{E}_t [KL(\pi_{old}||\pi_\theta)] \leq \delta$.

where $\delta$ is the hyperparameter that determines the trust region. $A_t = R_t - V(s_t)$ is the advantage which is calculated by subtracting the return with a baseline. A value estimation $V(s_t)$ provided by a critic is used as the baseline.

2) Discounted return: The total return is used as an evaluation of performance and is determined by calculating the discounted reward,

$$R_t = \sum_{l=0}^{T-t} \gamma^l r_{t+l},$$

where $T$ is the total number of samples in an episode and $\gamma$ is the discount factor. The half-life of future rewards is used as a reference to decide the value of the discount factor $\gamma$. For balancing, a time horizon between 0.5s and 2s is close. With a frequency of 25Hz, 0.5s equals to 13 time steps. We choose the discount factor in a way that the half-life of the future reward occurs at 0.5s, meaning that the accumulated discount factor equals to 0.5 at 13 time step $\gamma^{13} = 0.5$, hence $\gamma \approx 0.95$.

3) Generalized Advantage Estimation: With the policy gradient method and a stochastic policy, we obtain an unbiased estimate of the gradient of the expected total reward, however the estimated policy gradient has high variance. An effective variance reduction scheme for policy gradients called Generalized Advantage Estimator (GAE) was proposed in [26]. GAE interpolates between a high bias and low bias estimator through the parameter $\lambda \in [0, 1]$. One can adjust the bias/variance trade-off by tuning $\lambda$. The GAE for the parameters $\gamma, \lambda$ at time $t$ is:

$$A_t^{GAE(\gamma, \lambda)} := \sum_{l=0}^{\infty} (\gamma \lambda)^l \delta_{t+l}$$

where $x_{CP}$ is the CP, $x_{COM}$, $\dot{x}_{COM}$ is the CoM position and velocity, $z_c$ its height, and $g$ the gravitational constant.

When the CP is within the support polygon, the robot does not need to perform any footstep to maintain balance. Knowing the feet dimensions and therefore the support polygon, the theoretical maximum impulse which can be rejected without foot-stepping can be approximated as follows [11]:

$$J_{\text{reject}} = m \sqrt{\frac{g}{z_c}} \Delta_{\text{COP}}.$$
a sense that it has spring damping properties. A comparison
between directly using torques and a PD controllers to
compute the torques for certain motor tasks was conducted
in [28] and showed that using a PD controller improved
learning speed and overall performance. The resulting torque
is computed as:
\[ u = K_p(q_{\text{target}} - q_{\text{measured}}) - K_dq_{\text{measured}}, \]  \( \text{(7)} \)
where \( K_p, K_d \) are the PD gains respectively, \( q_{\text{target}} \) is the
targeted joint angle, and \( q_{\text{measured}}, \dot{q}_{\text{measured}} \) are the measured
joint angles and velocities respectively.

C. Observation space and action space
Input states are chosen in a way such that they can be
acquired by sensors on the robot with minimal amount of
computation. Immeasurable states are inferred or estimated
by the Neural Network. All the sensory information provided
as the observational input for the policy is heading-invariant.
For balancing, the rotation along the direction of the gravity
vector is irrelevant to the balancing state, therefore informa-
tion about the heading is not needed as feedback, i.e.
the policy will perform the same action regardless of global
yaw orientation. In order to make the state observation
heading invariant, we preprocessed the state by performing
transformation of the observations along the gravity axis.
The state \( S \in \mathbb{R}^{17} \) consists of joint angle and velocity,
pelvis states (translational and angular velocity, orientation),
CoM states (translational velocity and position w.r.t. pelvis),
ground contact force, torso position w.r.t. pelvis, and foot
position w.r.t. pelvis. The observation states are sampled
at a frequency of 500Hz and are filtered by a first-order
Butterworth filter with a cut-off frequency of 10Hz.
Under consideration of computation efficiency, we mini-
mize the size of action space. A minimum of 11 joints
that includes only roll and pitch joints are sufficient for
balancing. The action space \( A \in \mathbb{R}^{11} \) of the policy describes
the motion of the joint angles. The upper body joints are
locked in a nominal position, while for the lower body, only
the pitch joint and roll joint are controlled. The controlled
joints therefore are: torso pitch, left and right hip pitch &
roll, knee pitch, and ankle pitch & roll.

D. Design of reward function
The design of the reward function is a crucial part in re-
forcement learning as the reward governs the outcome be-
behavior. The reward design follows a similar design rule as in
[27]. Balancing can be divided into four subtasks: regulating
upper body pose, regulating CoM position, regulating CoM
velocity, and regulating ground contact force. The individual
reward is calculated using
\[ \tilde{r}_i = \exp(-\alpha_i(x_{\text{target}} - x)^2), \]
with \( x_{\text{target}} \) as the desired value, \( x \) as the real value, and
\( \alpha_i \) as the normalization factor. These are then weighted by
\( w_i \). Furthermore, additional penalty terms are added: ground
contact regulation, loss of contact with the ground, and when
other parts of the body other than the foot make contact with
the ground. We also apply a penalty for the control effort
used. The overall reward can be viewed as a sum of the
individual reward terms:
\[ r = r_{\text{pose}} + r_{\text{CoM, pos}} + r_{\text{CoM, vel}} + r_{\text{GRF}} +
\]
\[ r_{\text{contact}} + r_{\text{power}}. \]  \( \text{(8)} \)
1) Upper body pose modulation: The upper body pose
is represented by the pitch and roll angle of the torso and
pelvis. The desired orientation for the pitch roll angle for
both pelvis and torso is 0, which is the orientation of the
upper body when it is upright:
\[ r_{\text{pose}} = w_{\phi_{\text{target}}} \tilde{r}_{\phi_{\text{target}}} + w_{\phi_{\text{pelvis}}} \tilde{r}_{\phi_{\text{pelvis}}} +
\]
\[ w_{\phi_{\text{torso}}} \tilde{r}_{\phi_{\text{torso}}} + w_{\phi_{\text{pelvis}}} \tilde{r}_{\phi_{\text{pelvis}}} \]  \( \text{(9)} \)

2) CoM position modulation: The reward term for CoM
modulation is decoupled into horizontal and vertical com-
ponents. For the horizontal CoM position, the target position
is the center of the support polygon to provide maximum
disturbance compensation. For the vertical CoM position, the
robot should stand upright and maintain a certain height,
\[ r_{\text{CoM, pos}} = w_{x_{\text{CoM}}} \tilde{r}_{x_{\text{CoM}}} + w_{z_{\text{CoM}}} \tilde{r}_{z_{\text{CoM}}}. \]  \( \text{(10)} \)
3) CoM velocity modulation: Similar to the CoM position,
the reward for CoM velocity is decoupled into two compo-
nents: velocity in the horizontal and vertical planes. The
CoM velocity is represented in the world frame. The desired
vertical CoM velocity is 0 as we want to minimize
vertical movement, while the desired velocity for horizontal
CoM velocity is derived from capture point. The Capture
Point is only valid when the robot has contact with the
ground with no slipping, therefore when the robot is in the
air, the reward term for horizontal CoM velocity \( \tilde{r}_{x_{\text{CoM}}} \)
is deemed invalid and is set to 0:
\[ r_{\text{CoM, vel}} = \begin{cases} 
0 & \text{foot contact} \\
\tilde{r}_{x_{\text{CoM}}} & \text{no foot contact.} 
\end{cases} \]  \( \text{(11)} \)
4) Contact force modulation: The force has to be evenly
distributed between both feet for a stable robust balance. The
total mass of 137kg yields a force of 671.3N for each foot:
\[ r_{\text{GRF}} = w_{F_{\text{left}}} \tilde{r}_{F_{\text{left}}} + w_{F_{\text{right}}} \tilde{r}_{F_{\text{right}}}. \]  \( \text{(12)} \)
5) Ground contact: When the robot is standing, only the
feet are in contact with the ground, therefore a penalty is
introduced whenever both feet lose contact with the ground
or body parts other than the feet make contact with the
ground:
\[ r_{\text{contact}} = \begin{cases} 
-2, & \text{if no foot contact with ground} \\
-10, & \text{if upper body contact with ground.} 
\end{cases} \]  \( \text{(13)} \)
6) Power consumption: The power consumption is cal-
culated as follows:
\[ r_{\text{power}} = w_{\text{power}} \sum_{j=0}^{11} \| \tau^j \cdot \dot{q}^j \|, \]  \( \text{(14)} \)
with \( \tau^j \) is the torque applied on individual joints, and \( \dot{q}^j \) is
the joint velocity.
Fig. 4: Overview of neural network structure.

### E. Network structure

The stochastic policy $\pi_\theta(a|s)$ is represented as a conditional Gaussian policy $\pi_\theta(a|s) \sim N(\mu_\theta(s), \sigma_\theta)$. The mean of the Gaussian policy is parametrized by a neural network with parameters $\theta$, the covariance of the Gaussian policy is independent from the neural network and is maintained by a separate set of parameters $\sigma_\theta$.

The critic $V_\phi$ parametrizes the value function with a separate set of neural networks using parameters $\phi$. Both the actor and the critic are parametrized by a fully connected feedforward neural network that consists of 3 hidden layers with 100, 50 and 25 neurons for each layer. The actor network uses tanh activation for the hidden layers while the critic uses ReLU activation for the hidden layers. The output of both network is produced by linear activation.

The actor network is trained to maximize the reward function (section IV-D), while the critic network is trained by minimizing the loss function $L_V(\phi)$:

$$L_V(\phi) = E_s \left[(V(s_t) - y_t)^2\right], \quad (15)$$

with the discounted Return $y_t$ (eq. 3), value function $V(s_t)$.

### F. Exploration during training

In order to learn a policy capable of withstanding large push disturbances, sufficient exploration during the training phase needs to be provided. Therefore, in addition to the stochastic policy, random forces are applied on the pelvis during the training. From Capture Point theory, the maximum disturbance in the sagittal plane without foot-stepping is $53Ns$. The bounds of the training disturbances is chosen to be $[53 \times 0.5Ns, 53 \times 2Ns]$. The orientation of the force in the horizontal plane and the disturbance in the bound are randomized. Disturbances are applied to the robot multiple times during each trial, with 5s interval between subsequent push disturances for push recovery.

### G. Learning Algorithm

Due to the structure and choice of our framework, the learned policy is independent of the type of learning algorithm. We trained a policy for maintaining balance via TRPO, PPO, and DDPG, and found similar resulting behavior (cf. Table I). All four balancing strategies (Fig. 1) emerges regardless of the DRL algorithm used. However, from our simulations, TRPO is able to achieve higher rewards and is able to withstand higher impulses. Figure 5 shows the learning curves for the policies learned in Table I. DDPG is trained off-policy and utilizes a replay buffer, whereas TRPO and PPO are trained on-policy batch-wise, which makes it difficult to directly compare.

All three DRL algorithms are able to learn a feasible balancing policy. The difference in performance can be attributed to the randomness in different trials of training and hyperparameters. Training is performed entirely on a single Intel Core i7-6700K with 4.0 GHz and converges in two days.

TABLE I: Maximal rejectable impulses for the various learning algorithms without taking steps.

<table>
<thead>
<tr>
<th>Learning algorithm</th>
<th>Sagittal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRPO</td>
<td>240</td>
<td>78</td>
</tr>
<tr>
<td>DDPG</td>
<td>75</td>
<td>160</td>
</tr>
<tr>
<td>PPO</td>
<td>192</td>
<td>36</td>
</tr>
<tr>
<td>Baseline from (6)</td>
<td>53</td>
<td>78</td>
</tr>
</tbody>
</table>

### V. Results

In the following, a series of test scenarios are presented to evaluate the performance of the control policy acquired by the deep reinforcement learning agent. Furthermore, we show its robustness to external disturbances, as well as noise in the observation (measurement) and action (actuation) spaces. Next, a comparison against traditional methods from other works is made. Lastly, the physical validity of the generated motions is analysed and verified. Please refer to the accompanying video for the results (cf. https://youtu.be/43ce2cLV0ZI).
A. Horizontal push on pelvis

Horizontal disturbances were applied on the pelvis during the training phase, and therefore the DRL agent should be able to learn to withstand such type of disturbances. The robot exhibits different behavior depending on the amount of disturbance applied (Table II, Fig. 6). Different control strategies emerge and range from generating ankle torque to shift the COP (ankle strategy), generating angular momentum (hip strategy), over tilting the foot to dissipate the disturbance (foot tilt strategy), to taking a step to recover from the large push (stepping strategy). The magnitude of the lateral pushes, for which the robot is capable of withstanding, is significantly smaller than in the sagittal plane. This is due to the fact that the support leg will block the swing leg in the lateral direction, limiting the range for leg movement. Dealing with this problem involves either jumping to take a step, or crossing the legs, which, due to the kinematic constraints, is not possible for Valkyrie. These jumping manoeuvres were not learned by the policy, as high velocities in the CoM resulted in lower rewards.

From the CoM position (Fig. 6a) and the pelvis orientation (Fig. 6b) it can be inferred that the robot is standing still after 3s. As can be seen by the eight flat plateaus in Figure 6(c), eight steps are taken in order to deal with a impulse disturbance of 240Ns at the pelvis. After the eighth step the robot stands still in the nominal pose. For other horizontal pushes, the stepping behavior is similar.

<table>
<thead>
<tr>
<th>Emerging behaviour</th>
<th>24Ns</th>
<th>72Ns</th>
<th>240Ns</th>
<th>78Ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push direction</td>
<td>sagittal</td>
<td>sagittal</td>
<td>sagittal</td>
<td>lateral</td>
</tr>
<tr>
<td>Ankle strategy</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hip strategy</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Foot tilt strategy</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Stepping strategy</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

TABLE II: Emerging behavior for impulse disturbances of different magnitudes. A checkmark indicates that the respective strategy is applied in addition to the other marked strategies.

B. Force disturbance on other body segments

During the training phase only horizontal disturbances were applied on the pelvis. It is well known in machine learning that the test set should vary from the training set. Therefore, we also designed test scenarios which the DRL agent has never encountered before during training to see how well the policy generalizes.

In push recovery studies, the disturbance is usually applied near the CoM to avoid introducing any torque into the system, as it is more challenging to balance a robot with high amount of angular momentum. We are interested in how well the policy will perform when disturbance is applied on other parts of the body far away from the CoM. We chose three body parts for which a large torque and angular movements would result when force is applied on: the upper torso, leg thigh, and leg shank (Table III). The resulting motion for being pulled at the shank can be seen in Figure 7. In Figure 7a) six steps for recovering balance are observed. The support foot height, and roll and pitch angle relative to the ground can be seen in Figure 7b). Finally, the angular movement of the pelvis Euler angles (Fig. 7c) show that the robot recovers into an almost nominal pose after six steps.

<table>
<thead>
<tr>
<th>Body part</th>
<th>Max. impulse in [Ns]</th>
<th>Lever in [m]</th>
<th>Torque in [Nm]</th>
<th>Amount of steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper torso</td>
<td>120</td>
<td>0.32</td>
<td>320</td>
<td>6</td>
</tr>
<tr>
<td>Leg thigh</td>
<td>108</td>
<td>0.50</td>
<td>450</td>
<td>4</td>
</tr>
<tr>
<td>Leg shank</td>
<td>108</td>
<td>0.70</td>
<td>630</td>
<td>6</td>
</tr>
</tbody>
</table>

TABLE III: Maximum rejected impulse for different body parts.

C. Landing from height

A different type of impact is applied to the robot by dropping it from a height above the ground with the objective to land stably. Landing involves high impact and sudden changes in ground contact. Various control strategies involving the Zero-Moment Point (ZMP) or CP assume steady contact with the ground and, without a switching mechanism, fail to perform when the robot is in the air. This test scenario is used to test whether the policy can handle high impact and sudden change in ground contact and land stably.

The robot is capable of landing after being dropped from a maximum height of 0.55m above the ground. Furthermore, it is able to handle randomly initialized orientations of the pelvis within $\left[-5^\circ, 5^\circ\right]$ under a dropping height of 0.4m (with a leg length of 1m, this is a displacement of $0.087m = 1m \cdot \sin\left(5^\circ\right)$ compared to the initial position).

D. Combined test case

Lastly, a combined test case involving linear and angular momentum disturbances is designed. In this test scenario, we first apply a vertical force upward to lift the robot off the ground and then apply a horizontal force when the robot is in the air. As a result, the robot has to handle linear and angular momentum and sudden high impacts at the same time. The robot is able to recover for a vertical impulse of 500Ns, and a horizontal impulse of 70Ns. In order to deal with this combined disturbance, the policy used all four push recovery strategies: ankle, hip, toe, step. Apart from the physical impossibility of throwing a 137kg robot, the resulting joint torques, velocities are within the joint limits of the real Valkyrie (cf. Section V-G).

E. Robustness against noise in observation and action space

In real world applications, noisy measurements and actuations signals are a main contributor to the discrepancy between simulations and reality. In order to test our policy’s ability to be applied in the real world, its ability to handle noise both in action and observation space is tested. For this, a Gaussian distributed noise $d \sim N(\mu, \sigma)$ is added to both action space ($\mu = 0, \sigma = 0.1$), and state space
and D are obtained from real experiments, we show in the
Fig. 6: Resulting motions from impulse disturbance and balance recovery.

We showed successful balance recovery with a policy trained
next section that the generated motions are realistic and
within the real physical constraints.

Fig. 7: Resulting motions from an impulse disturbance at the shank. The robot takes 6 steps before standing stably.

($\mu = 0, \sigma = 0.5$). We found that the policy is able to handle
the ones presented in Table V.

G. Realism of generated motions

Despite learning is trained in a simulator, we emphasize re-
alistic motions by enforcing joint angle, velocity, and torque
limits, which are the same as on the real Valkyrie robot.
Therefore, the learned motion could be applied on the real
Valkyrie robot without violating physical constraints. Table
V compares the peak torques and velocities for different
scenarios. The chosen scenarios require the largest joint
torque for dropping and the largest joint velocities for taking
multiple steps due to large pushes at the pelvis. All other
presented test cases required less joint torque and velocity
than the the ones presented in Table V.

VI. CONCLUSION

In this work we proposed a learning framework which
is able to learn a versatile unified control policy via
Deep Reinforcement Learning. We found that the policy is able
to deal with different types of disturbances and has comparable
performance to conventional controllers. The policy acquired
is capable of functioning in unseen situations, demonstrating
that it is generalizing well over tasks. Furthermore, the pro-
posed learning framework is learning algorithm independent.
We showed successful balance recovery with a policy trained
with three of the state-of-the-art DRL algorithms: TRPO,
PPO, and DDPG. The emerging motions for push recovery

(a) CoM motion over time for multiple
forces. The CoM position of the 2000N is
scaled by 0.05

(b) Pelvis orientation over time.

(c) Foot and CoM movement for sagittal
push of 2000N.

(a) CoM and feet motion.

(b) Support foot behavior (swing foot not
depicted).

(c) Angular movement of the pelvis.

The normalized impulse is used for comparison between
the controllers of other works [10, 13, 29, 30] and the
learned policy (Table IV). We compared sagittal and lateral
pushes. For the sagittal push, two impulses are chosen such
that foot stepping occurs for the larger impulse (1.73Ns/kg),
while the smaller impulse (0.57Ns/kg) will result in a stra-
egy without stepping. By comparing the rejectable normal-
ized impulse of the strategies not taking a step (A, B, E, G), it
can be seen that our policy performs similar (E: 0.57Ns/kg,
G: 0.56Ns/kg) to the other controllers (A: 0.6Ns/kg, B:
0.52Ns/kg). For the strategies taking a step (C, D, F),
our policy is able to perform better (F: 1.73Ns/kg) than
the stepping controllers C (0.52Ns/kg) and D (0.6Ns/kg).
Albeit our results are obtained from simulation whereas C
and D are obtained from real experiments, we show in the
are similar to human motions demonstrating the ankle, hip, foot-tilting, and stepping strategy. We compared the learned policy against traditional push recovery controllers and found similar disturbance rejection capabilities.

**REFERENCES**


