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Knee joint muscles neuromuscular activity during load-carrying walking

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Abstract

OBJECTIVE: To investigate the effects of increasing load on changes in the muscle activity ratio and onset of vastus medialis (VM), vastus lateralis (VL) and biceps femoris (BF) during load-carrying walking.

MATERIALS AND METHODS: Sixteen strength-trained men performed an isometric test for knee flexion/extension using a dynamometer followed by walking with progressively increasing loads of up to 75% of their body mass (BM). During the isometric tests and load-carrying walking, electromyography (EMG) data were collected from the VM, VL and BF in both legs together with 3D kinematics.

RESULTS: Significant changes in the activity ratio were found for the VM/VL ($F_{3,93}$=5.92, p=0.0001) and VL onset ($F_{3,81}$=6.8, p=0.0004). Other parameters showed no significant differences. VM/VL was significantly reduced between the 50BM (mean ± SD: 0.89±0.4) and the 75BM condition (0.81±0.3). VL onset was significantly accelerated between the BM (26.11±8) compare and the 25% BM (19.47±9), 50% BM (21.21±10) and 75% BM (15.45±6) conditions.

CONCLUSION: Load-carrying walking is an exercise and movement activity that increases the activity of VL more than the activity of VM and accelerates the VL action together with the increased load, which can negatively influence knee stability. The VM/VL ratio and onset is equal when walking under weight-bearing conditions. The inter-muscular coordination is changed due to the increased load in complex movements even in individuals with high level of neuromuscular adaptation.

INTRODUCTION

Neuromuscular activity play crucial role in joint protection during frequent and intensive movements. Both intramuscular and inter-muscular coordination are involved in joint centration, which is primary involuntary action. From this point of view, knee stability can be disrupted by muscle imbalance between the vastus medialis oblique (VM), vastus lateralis (VL) (Bennell *et al.* 2010; Irish *et al.* 2010; Segal *et al.* 2010) and biceps femoris (BF) (Kong & Burns 2010; Holcomb *et* *al.* 2007) during complex movements. This instability could lead to pathologies, such as patellofemoral pain syndrome (PFPS) (Gilleard *et al.* 1998; Powers *et al.* 1996), and could be described by the activity ratio level as in the Sian study (Irish *et al.* 2010) or an imbalance in activation timing (Gilleard *et al.* 1998; Van Tiggelen *et al.* 2009) as an appropriate muscle involvement with a hypothetical activity ratio of VM/VL is approximately 1:1 (Irish *et al.* 2010).

One of the traditional methods for evaluating knee stability is the hamstring/quadriceps strength ratio (H/Q) (Danneskiold-Samsoe *et al.* 2009; Harbo *et al.* 2012; Kong & Burns 2010). This ratio has been studied in physiotherapy to understand the principles of knee stability and in sport sciences to improve strength training programs. This strength ratio describes the relationship between knee flexors and extensors, but it has limitations in evaluating the action of VM and VL. The strength ratio is usually more general than muscle activity because it is measured with standardised dynamometers with predefined movement tasks (angle and speed specific tasks) in contrast with muscle activity, which is measured during natural human performance. The muscle activity ratio can help evaluate natural movement and describe differences in individual muscles parts.

The Sian study (Irish *et al.* 2010) evaluated the VM/VL electromyography ratio activity during double leg squats with isometric hip adduction and the lunge exercise, when lunge exercise is complex movement improving stability (Kobesova *et al.* 2012) and produces the closest ideal ratio of 1:1. Other studies demonstrated greater VM involvement in resistance hip adduction exercises (Hanten & Schulthies 1990) and squats with hip adduction (Felício *et al.* 2011). All of these studies evaluated exercise under weight-bearing conditions, but muscle action could varied due to exercise intensity. Exercise intensity is an important part of strength training, and it is important to choose an exercise that has the targeted muscle involvement during weight-bearing and external load conditions. After surgery, knee pain effects have to also be taken into account with increasing load (Bandholm *et al.* 2014) or when finding that knee pain does not decrease thigh muscle strength in adolescents (Rathleff *et al.* 2013).

Most previous studies have found that either higher VL activation or early delayed VM activation during a performed movement are reasons for knee instability, and these may result in PFPS (Van Tiggelen *et al.* 2009; Powers *et al.* 1996). Thus, in these cases, strength training should lead to more VM than VL involvement. For strength training, the best exercise is one that activates VM during low intensity and increases the activation of VM with an increased load. With regards to timing, it is best to achieve parallel action for those muscle groups.

Tab. 1. Description of research group.

Variable	Participant (n=16)
Age (years)	30.5±3.2
BM (kg)	84.61±9.88
Height	181.78±6.28
Trainings/weak	2.32±1.41

Physiotherapeutic exercises are not usually complex exercises. Complex exercises are considered to be most effective for strength training for both experienced individuals and the general population without pathologies (Siff 2003). In addition, isolated exercises could have stimulating effects on the muscle involvement in just one joint. Complex exercises, such as squats, lunges or step ups, are usually difficult in term of exercise techniques, and their inclusion in training programs requires strength training preparation.

A popular training system is “functional training,” which attempts to use frequently used complex movement patterns. Previous studies have investigated the muscle involvement in complex exercises, such as split squats, lunges, or step up/downs (Boudreau *et al.* 2009; Distefano *et al.* 2009; Andersen *et al.* 2006; Selkowitz *et al.* 2013). Frequently used movement patterns include walking, which is used in a modified variation for strength training. A popular exercise is load-carrying walking, which is a commonly used strongman exercise performed in a general strongman training sessions (Winwood *et al.* 2011). This exercise may have benefits not just for strongmen but also the general population. The beneficial purpose of this exercise in the general population is that walking is a frequently performed daily movement and is a basic action for human locomotion.

The aim of this study was to investigate the VM, VL and BF peak activity ratios together with their timing (onset) and knee flexion/extension degrees during load-carrying walking at different intensities. The assumption was that the peak activity ratio of VM/VL would change due to increased loads. The assumption for changes in the VM and VL timing was unclear, but there was the expectation that knee kinematics would not change. BF/VL, VM/BF ratios and other BF values were measured as a control parameter, but BF is also involved in knee stability as a part of hamstrings. Therefore, there may be related effects on hamstring action toward quadriceps action. Load-carrying walking is used as exercise during “functional” training, but the effects of this exercise on leg muscle activation is unclear. The results of this study should lead to recommendations for the use of this exercise in strength training and reconditioning.

MATERIALS AND METHODS

The study group consisted of sixteen strength-trained men (Table 1) with competition or recreational experience in power lifting who were recruited during October 2013. All participants were in actual strength training programs, with a minimal amount of two lower limb strength training per week. All participants lacked any pathologies or injuries. Written informed consent was provided by the participants, and the testing protocol was approved by the local Committee of Ethics at Palacky University in Olomouc in accordance with the ethical standards of the Helsinki declaration of 1983. All participants were informed about the testing protocol and all aspects of the study when they signed the written informed consent form for the study and were shown the testing protocol.

The procedure took place in a biomechanics laboratory at Palacky University, Faculty of Body Culture between October and December 2013. Before the 50-minute long measurement of participants, a warm up procedure was performed, including 5 min of ergometer cycling and load-carrying walking trials. Isometric tests of participants were performed with a dynamometer IsoMed 2000 (D&R Ferstl GmbH, Hemau, Germany) together with a surface electromyography (EMG) for the VM, VL and BF to estimate the maximal value of the EMG activity, that is, the maximal isometric voluntary contraction (MVIC). After the isometric test, load-carrying walking was performed. The carried load was progressively increased (by 25%) up to 75% of the body mass (BM) of the participant. During isometric tests and walking with external loads, electromyography data were collected from the VM, VL and BF in both legs with a Noraxon 1400A device (Noraxon; Scottsdale).

After the MVIC estimation, participants were taped with 3D markers, and performed three load-carrying walking exercise trials with an external load of 0, 25, 50 and 75% of body mass (BM, 25BM, 50BM, 75BM conditions). During the gait cycle (GC), 3D kinematic data were collected with a Vicon-612 six camera infra-red motion analysis system (Oxford Metrics, Oxford, UK). Raw EMG signals were recorded by six leads with a 1000 Hz frequency. Two bipolar surface electrodes (adhesive disposable electrode – Kendall) were taped on each muscle with a 24 mm inter-electrode distance. The input impedance was greater than 10 MΩ at 100 Hz, and common mode rejection 80 db.

The electrodes for VM were placed over the distal third of the muscle belly and were oriented 55° to the vertical (Figure 1). The electrode for VL was placed over the muscle belly in the distal third and was oriented 15° to the vertical (Figure 1). The electrodes for BF were placed over the distal third of the long head muscle belly. The ground electrode was placed over the tibia bone.

To obtain a baseline EMG signal, subjects performed two times 5 s isometric contractions on the dynamometer for flexion/extension. VM, VL and BF MVICs were performed in the standard sitting position with 75° knee flexion (Figure 1). The backrest of the dynamometer seat was set to an angle of 75°, and the angle in the hip joint was 100°. Subjects were fixed by belts in the pelvic and thigh region on the lower limbs tested. Adjustable straps and pads were placed on the shoulders, and participants held hand grips along the seats. The mechanical axis of the dynamometer was aligned with the knee axis according to the standard position for knee flexion/extension

Kinematic data were recorded at 200 Hz using a six-camera VICON infra-red motion analysis system. Cameras were spaced around the walking track with two force plates (Kistler Instrumente, Winterthur, Switzerland) in the middle.

Force plates and EMG output were connected to the Vicon software. Reflective markers 19 mm in diameter were bilaterally attached to the subject's skin over the following landmarks: the anterior superior iliac crest, posterior superior iliac crest, lateral thigh, lateral femoral epicondyles, tibias, lateral malleolus, heels, and metatarsal head of the second toe.

The gait cycle (GC) was computed in the same manner as that for regular walking. A one-step cycle was estimated as heel to heel contact of one lower limb.

Fig. 1. Body position during maximum voluntary isometric test (MVIC) and quadriceps electrodes placement.

Heel strike was assessed on a force plate when the vertical force reached 20N. This process allowed for the exact determination of the walking pattern for every individual. From each attempt, analysis of one step of the right and left legs was chosen with data from the EMG, 3D analyses and force plates. Each measured condition was performed 3 times with a fully detected execution of load-carrying walking for statistical analyses.

EMG data were band-pass filtered (10–500 Hz) and smoothed using a root mean square (RMS). The EMG signal was normalised to the maximum EMG value from isokinetic tests for the %MVIC. The mean amplitude was chosen to describe muscle activation ratios for the VM, VL, and BF (VM/VL, VM/BF, and BF/BVL). EMG activity onset was set at the first peak amplitude (sliding mean from a peak 25 ms window) and expressed as a percentage of the GC when the first peak occurred: VM_{onset}, VL_{onset}, and BF_{onset}. From knee kinematics, the degree of flexion/extension at the EMG peak was used: VM knee flexion at peak time (VM_{flex}), VL knee flexion at peak time (VL_{flex}) and BF knee flexion at peak time (BF_{flex}).

Statistical analyses

For statistical analysis, repeated-measures analysis of variance (ANOVA) was used for selected dependent variables at a significance level of $p<0.05$ for all of the statistical procedures. Huynt-Felt adjustment (ε) was counted to estimate the variables sphericity. The levels of increased load were used as related groups and EMG with kinematics were used as the dependent variables. The results are reported as the mean and the standard error (SD) for the measurements in the text, tables and graphs. The intraclass correlation coefficient (ICC) across 3 trials for each individual was counted to confirm whether the EMG measurements were stable within a subject. Tukey's post hoc test was used to determine settings for significant differences. STATISTICA version 12 (StatSoft, Inc., Tulsa, OK, USA) software was used for statistical analysis.

RESULTS

The reliability analyses across 3 trials for individuals resulted in ICC values ranging from 0.42 to 0.92. The ICC value for each parameter and load condition is shown in Table 2. High (ICC value: 0.6–0.8) or very high reliability (ICC value: 0.8–1) (Chandler & Brown 2008) were found for most of VM and VL variables. Moderate reliability (ICC value: 0.4–0.6) (Chandler & Brown 2008) was found for the BF variables BF_{flex} and BF_{onset}. In addition ε value didn't decrease under 0.75 for any dependent variable.

In the GC, the VM_{onset} was found to range between 28.6 and 21.1% of step. BF_{onset} was found to have a range between 34.3 and 43.5%, which corresponds to the stance phase when propulsion is generated. VL_{onset} was found to be 19.22 and 21.2% of the gait cycle for 25BM and 50BM, but for 75BM, the VL_{onset} was 15.45% of the GC. The degree of knee flexion at peak activity was slightly different for all load conditions, and the peak activity usually had a lower degree of flexion due to increased load. All of the means are shown in Table 2.

Repeated measures ANOVA showed significant differences in VM/VL ($F_{3,\ 93}$=5.92 p=0.0001) and VL_{onset} ($F_{3,\ 81}$=6.8, p=0.0004) Table 3 and Figures 2–3. VM/VL was significantly lower in the 50BM (mean ± SD: 0.89±0.4) compare with the 75BM condition (mean ± SD: 0.81±0.3) Table 3 and Figure 2. *Post-hoc* tests for VM/VL (HSD=0.06) showed no significant difference between the 25BM and 50BM load conditions. VL_{onset} was significantly accelerated in the BM (mean

Tab. 2. Mean values and reliability for observed parameters (n=32).

Loading condition	25BM		50BM		75BM	
	Mean ± SD	ICC	Mean ± SD	ICC	Mean ± SD	ICC
VM/VL	0.94±0.40	0.84	0.89±0.38	0.90	0.81±0.28	0.89
VM/BF	1.40±1.16	0.92	0.88±0.61	0.76	0.70±0.35	0.77
BF/VL	1.02±0.73	0.60	1.45±1.04	0.75	1.62±0,9	0.64
VM_{onset} (%CG)	28.60±14	0.75	21.20±13	0.82	21.10±13	0.78
VL_{onset} (%CG)	19.22±9	0.87	21.20±10	0.80	15.45±6	0.89
BF_{onset} (%CG)	43.50±19	0.42	38.90±14	0.66	34.30±16	0.46
VM_{flex} (°)	18.20±8	0.70	15.10±8	0.89	13.70±10	0.81
VL_{flex} (°)	19.18±17	0.81	15.75±7	0.85	12.10±8	0.78
BF_{flex} (°)	19.42±9	0.49	18.75±10	0.45	14.52±5	0.79

Legend: BM, body mass; VM, vastus medialis obliqus; VL, vastus lateralis; BF, biceps femoris; %MVIC, percent of maximum voluntary isometric contraction; VM/VL activity ratios between VM/VL in %MVIC; VM/BF, activity ratios between VM/BF in %MVIC; BF/VL, activity ratios between BF/VL in %MVIC; VM_{onset}, VM onset time expressed as percent of the gait cycle; VL_{onset},VL onset time expressed as percent of the gait cycle; BF_{onset}, BF onset time expressed as percent of the gait cycle; VM_{flex}, VM knee flexion at peak time; VL_{flex}, VL knee flexion at peak time; BF_{flex}, BF knee flexion at peak time; SD, standard deviation; ICC, intraclass correlation coefficient;

± SD: 26.11±8) compared with the 25BM (mean ± SD: 19.47±9), 50BM (mean ± SD: 21.21±10) and 75BM (mean ± SD: 15.45±6) conditions (Table 3 and Figure 3). Other ANOVA results showed no significant difference, which most often was due to the low observed power alpha value (Table 3). VM/BF was not found to be a significantly different for higher values in post hoc testing HSD (HSD=0.51), and there was lower reliability for BF values.

DISCUSSION

Our results indicate that load-carrying walking is an exercise that changes the VM/VL ratio and accelerates the timing of VL activation together with increased loads compared to walking under weight-bearing conditions. This timing change, which accelerates VL activation, is considered to be negative for knee stabilisation (Irish *et al.* 2010; Felício *et al.* 2011). In the context of our results, this VL peak acceleration is not followed by VM peak acceleration. Thus, there was an observed VM delay for the 75BM load condition. This generally negative effect is likely to be worse for inexperienced individuals. The strength trained men as research group were recruited by purpose, because this specific population has previously been reported for high neuromuscular adaptation, when strength training performed twice a week led to large increases in the maximal voluntary activation of VL, VM muscle during both isometric and concentric knee extension actions

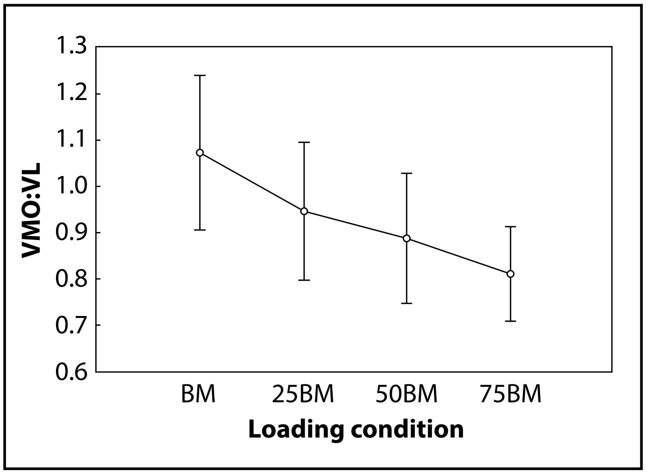

Fig. 2. Graph from repeated measures ANOVA result for VM/VL. VM/VL, activity ratios between VM/VL (%MVIC), BM, Body mas; 25BM, load condition of 25% of BM; 50BM, load condition of 50% of BM; 75BM load condition of 75% of BM; 95% confidence interval.

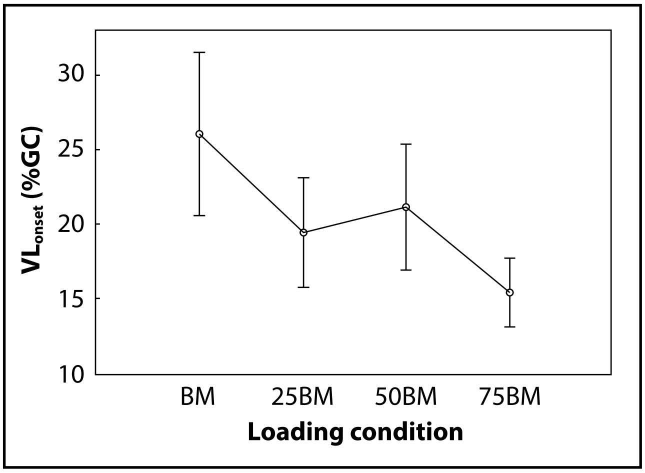

Fig. 3. Graph from repeated measures ANOVA result for VL$_{\%GC}$. VL$_{onset}$ VL onset time expressed as percent of the gait cycle, BM, Body mas; 25BM, load condition of 25% of BM; 50BM, load condition of 50% of BM; 75BM load condition of 75% of BM; 95% confidence interval.

Tab. 3. ANOVA results for each parameter.

Loading condition					**0 BM**	**25 BM**	**50 BM**	**75 BM**
	F	***p*-value**	**α**	**HSD**	**Ø**	**Ø**	**Ø**	**Ø**
VM/VL	$_{(3, 93)}$ 5.9	0.0001	0.94	0.06	1.08	0.95	0.89	0.81
VM/BF	$_{(3, 84)}$ 6.3	0.0065	0.95	0.51	1.61	1.02	1.45	1.62
BF/VL	$_{(3, 81)}$ 2.2	0.0920	0.54	0.87	0.93	1.5	0.88	0.70
VM$_{onset}$	$_{(3, 81)}$ 3.2	0.0250	0.73	10.3	23.0	29.5	21.2	21.1
VL$_{onset}$	$_{(3, 81)}$ 6.8	0.0004	0.97	6.50	26.1	19,4	21.2	15.4
BF$_{onset}$	$_{(3, 84)}$ 1.2	0.3185	0.30	12.7	40.4	43.5	38.9	34.3
VM$_{flex}$	$_{(3, 81)}$ 2.9	0.0370	0.68	5.71	13.5	18.2	15.1	13.7
VL$_{flex}$	$_{(3, 81)}$ 2.1	0.0995	0.53	5.67	17.6	19.2	15.8	12.1
BF$_{flex}$	$_{(3, 81)}$ 3.5	0.0182	0.76	5.37	15.3	19.4	18.8	14.5

Legend: BM, body mass; VM, vastus medialis obliquus; VL, vastus lateralis; BF, biceps femoris; %MVIC, percent of maximum voluntary isometric contraction; VM/VL, activity ratios between VM/VL %MVIC; VM/BF, activity ratios between VM/BF %MVIC; BF/VL, activity ratios between BF/VL %MVIC; VM$_{onset}$, VM onset time expressed as a percentage of the gait cycle; VL$_{onset}$,VL onset time expressed a percentage of gait cycle; BF$_{onset}$, BF onset time expressed as a percentage of the gait cycle; VM$_{flex}$, VM knee flexion at peak time; VL$_{flex}$, VL knee flexion at peak time; BF$_{flex}$, BF knee flexion at peak time; SD, standard deviation; HSD, honestly significant difference (Tukey); Ø, average;

(Häkkinen *et al.* 2001) and RMS value (Dasteridis *et al.* 2012). The participants in this study are well-trained individuals who are experienced in exercise with submaximal and maximal loads; therefore, their MVICs achieved higher results (Maeo *et al.* 2013), and they had a higher level of inter-muscular coordination. The same effect during load-carrying walking is also expected during daily movements, such as carrying loads in the general population. However, common daily walking movements did not demonstrate the high EMG activity (Tikkanen *et al.* 2013) as reached with loads.

Interesting results were shown during gait cycle kinematics as the VM peak was observed to be approximately 30% of the step cycle. For load-carrying walking with 75BM, VL peak activation was observed at 15% of the gait cycle, which is usually the landing part of walking. With regards to knee stabilisation, it could be assumed that VL is likely activated at the right time to retract the patella but VM was delayed for that action or that the VM action was not as accelerated as it should have been. The activity of BF was included as a reference or control parameter, which could refer to the parallel effect of hamstring action. Our results showed no significant difference in BF, meaning that changes in quadriceps involvement did not transfer into hamstring action.

In a previous study (Powers *et al.* 1996) using both kinematics and EMG, significant changes were not found in VM or VL activation based on activity conditions. This contradiction may be the result of progressively increasing the load and using the VM/VL ratio in this study. Other contradictions exist in studies evaluating the onset of the activation of VM and VL (Correa *et al.* 2002; Herrington & Pearson 2006a), and those studies did not demonstrate differences in VM and VL timing during a variety of exercise tasks. This difference could be because our study evaluated onset activation based on the first peak time. In contrast, this study is in agreement where the external load (Herrington & Pearson 2006b) or VM/VL ratio was used (Irish *et al.* 2010).

Our results do not indicate that load-carrying walking is a dangerous exercise, but there may be negative effects when this exercise dominates during strength training periods or early in reconditioning. There are many ways to avoid the negative effects of an exercise in a training session or training program. If load-carrying walking is used, negative effects can be compensated for by other exercises involving more VM action, as mentioned in studies focused on PFPS (LaBrier & O'Neill 1993; Crossley *et al.* 2001). Another way to compensate for negative effects is the pre-activation of VM prior to performing load walking.

A limit of this study is the increase in load, which can vary between individuals also due to the genetics profile (Petr *et al.* 2014). To standardise the increased loads, the participants used BM. In strength training, it is more appropriate to use the repetition maximum (RM) protocol (Siff 2003). For load-carrying walking, it is unusual to use RM because dumbbells have to be carried and not lifted. In addition, the exercise technique could be influenced by many factors, such as grip or spine position. Participants in this study were instructed to walk with their shoulders retracted and in a natural step cycle. When individual kinematic change errors are detected, such as sliding or floor hits, attempts were excluded from measurements. Other limits include the use of peak EMG amplitude for onset value because there may be qualitative differences in the three SD EMG values, anyway muscular activity onset is probably the best EMG outcome, therefore this parameter is used in previous studies (Fanta *et al.* 2013). The peak EMG value was chosen because the peak task may be a better reference for strength activity and the ability of the peak task to compare the timing of first peak activation, which would be more complicated if mean EMG task was used.

CONCLUSION

Load-carrying walking is an exercise and movement activity that increases the VL involvement with an increased load by increasing the activity level and achieving an earlier VL peak, which can negatively influence knee stability. Therefore, this exercise should not be performed by individuals with VM-VL imbalance. It is recommended to compensate for load-carrying walking with exercises that prefer VM activation, such as lunges or squats with isometric adduction. The VM/VL ratio and onset is equal during walking under weight-bearing conditions. In general meaning the inter-muscular coordination is changed due to the increased load in complex movements even in individuals with high level of neuromuscular adaptation.

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