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Mechanics of the Fouetté turn

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Abstract: 228 words Article: 3007 words

2	The Fouetté turn in classical ballet is performed repeatedly on one leg with swinging of the
3	free limbs, producing a continued sequence of turns with one turn leading into the next. The
4	purpose of this study was to determine the possible time history profiles of the twisting
5	torque between the supporting leg and the remainder of the body that will allow continued
6	performances of the Fouetté turn. Simulations were performed using a model which
7	comprised the supporting leg and the remainder of the body to find torque profiles that
8	maintain the initial angular velocity so that the state after one revolution is the same as the
9	initial state. The solution space of torque profiles was determined for various rotation times
10	and coefficients of friction between foot and floor. As the time for one revolution became
11	shorter the solution space became smaller and for a given turn time there was a lower limit
12	on the coefficient of friction. As the frictional coefficient became smaller the solution space
13	became smaller and for a given coefficient there was a lower limit on the turn time. Turns of
14	a given tempo can be performed on floors with different friction by modifying the twisting
15	torque profile. When a turn is completed with a net change in angular velocity this can be
16	compensated for in the next turn by adjusting the twisting torque profile.
17	KEY WORDS: Turn; Simulation; Angular Momentum; Ballet.

18 **PsycINFO classification code:** 2330, 3720, 3740

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19 **1. Introduction**

20	Skilled ballet dancers can continuously perform repeated Fouetté turns (Fig. 1)
21	and while there are various performance styles, such as Italian and Russian Fouetté
22	turns according to the ballet style of the dancer (Warren, 1990), the basic technique is
23	the same. The turn is started from one or two revolutions of the pirouette which is
24	initiated with both feet in contact with the floor to produce the initial angular
25	momentum. The dancer then keeps turning to music, swinging the arms and the free
26	leg while the supporting foot is stationary in full contact with the floor (Figs.1 A-D).
27	After the swinging, the dancer adopts the pirouette position during which the foot slips
28	(Fig.1 E-I) before starting to swing the free leg again (Fig. 1 J-K). The dancer regains
29	the angular momentum lost due to friction during the slipping phase by swinging the
30	free limbs when the foot is stationary, which enables the floor to exert a large frictional
31	torque T_F on the foot in the same direction as the swinging (Laws, 1984, 1998; Imura,
32	Iino, & Kojima, 2008). The dancer can keep turning for more than 30 revolutions by
33	repeating these movements.
34	The frictional torque T_F is the only external torque during the Fouetté turn and

consequently determines the changes in the angular momentum of the whole body.
 This frictional torque is dependent on the limiting frictional torque (limiting T_F) and

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37	the twisting torque T used to swing the free limbs. The supporting foot during the
38	Fouetté turn is essentially on tiptoe during the slipping or in full contact with the floor
39	when the foot stops turning.
40	*** insert Fig. 1 here ***
41	Dancers have to perform the Fouetté turn in time to the music in the
42	choreography, facing the front at the same position for the aesthetics of ballet (Laws,
43	1984). However, they sometimes turn to music tempo that is too fast or too slow and
44	struggle with performing successful turns. The friction coefficient between the shoes
45	and the floor of the performance stage may be different to that of the practice studio
46	and this will require technique to be modified.
47	The purpose of this study was to determine the possible time history profiles of
48	the twisting torque between the supporting leg and the remainder of the body that will
49	allow continued performances of the Fouetté turn. Techniques for coping with changes
50	in tempo and friction were also investigated.
51	
52	2. Methods

53 A computer simulation model of the Fouetté turn was used to investigate the 54 solution space of twisting torque profiles that permitted performances of successful

55	turns for various coefficients of friction between foot and floor and various time
56	periods of turn. The body (mass 49.5 kg) of a typical dancer who participated in a
57	previous study (Imura et al., 2008) was modeled as two cylinders (Fig. 2): the
58	supporting leg L and the remainder of the body B whose moment of inertia I_B about a
59	vertical axis changed according to the positions of the free leg and arms. The time
60	profiles of the foot radius r, the moment of inertia I _B , and the normal ground reaction
61	force N were based on experimental data from the study of Imura et al. (2008) and
62	were represented by joining adjacent maximum and minimum values using monotonic
63	quintic functions with zero first and second time derivatives at the endpoints (Fig. 3).
64	*** insert Fig. 2 here ***
65	The radius r was taken to be 0.12 m at the maximum when the supporting foot
66	is fully in contact with the floor and to be 0.05 m at the minimum when the dancer
67	stands on tiptoe (Fig. 3a). These bounding values were determined using the distance
68	between the toe and the center of the pressure (CoP) from the experimental data of
69	Imura et al. (2008). The foot radius time profile was matched to the experimental data
70	with time normalized to the turn time, recognizing that CoP locations were unreliable
71	when the normal reaction force was small.

The time profile of I_B (Fig. 3b) was calculated using the theorem of parallel

73	axes by scaling inertia data (Ae, Tang, & Yokoi, 1992) of a subject with similar body
74	mass as the model and using arm and leg positions based upon those exhibited in the
75	experimental study of Imura et al. (2008). The maximum and minimum I_B were
76	calculated to be 2.67 and 1.06 kg.m ² , respectively. The moment of inertia of the leg I_L
77	was assumed to be constant during the turn and was calculated to be 0.085 kg.m ² . The
78	normal ground reaction force N was determined by the following four values based on
79	experimental data from the study of Imura et al. (2008): 2.68 body weights at the time
80	of full foot contact, 0.0 body weights once slipping had started, 1.24 and 0.82 body
81	weights during slipping on tiptoe. It was assumed that the fitted profile was
82	symmetrical about the mid-turn time (Fig. 3c). The average N was one body weight
83	during one turn.
84	The friction coefficient μ between the shoes and the floor was estimated to be
85	0.2, calculated from the slipping phase of the experimental data of Imura et al. (2008)
86	using the equation $\mu = T_F / Nr$. The leg L was rotated further than B (Fig. 2) by 0.22
87	radians at the start of the turn according to the experimental data of Imura et al. (2008).
88	Simulations were performed for 1 s starting with the supporting foot in full
89	contact with the floor (Fig. 1A), with the requirement that the dancer rotates 2π in 1 s
90	using an appropriate twisting torque T. Three variables were used to define the time

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91	profile of T: T_{max} the initial (positive) torque to swing the free limbs and trunk, T_{min} the
92	(negative) torque which is maintained during the sliding to reverse the swinging, and
93	the time t_1 at which T becomes T_{min} . T_{max} , and T_{min} were joined by monotonic quintic
94	functions, assuming the profile of T to be symmetric since the dancer swings the limbs
95	at the end of the turn as at the start (Fig. 3d).
96	*** insert Fig. 3 here ***
97	The frictional torque T_F while the dancer is slipping can be assumed to be the
98	limiting T_F , which is the product of the friction coefficient μ , the normal ground
99	reaction force N, and the radius r of the foot contact area with the floor. When the foot
100	is stationary, the frictional torque T_F acting on the supporting foot is equal to T. The
101	frictional torque T_F was defined as T_F = T when $T \leq \mu Nr$ and T_F = μNr once L
102	slipped. Values for μ , N, r, I _B , I _L , and T were input into the equations of motion.
103	The angular momentum of the body B is given by $h = I_B \dot{\phi}_B$ where ϕ_B is the
104	angle turned by the body B. The torque T applied to the body B by the supporting leg L
105	is equal to the rate of change of h. Thus:
106	$T = I_B \ddot{\phi}_B + \dot{I}_B \dot{\phi}_B$ from which:
107	$\ddot{\phi}_{\rm B} = (T - \dot{I}_{\rm B} \dot{\phi}_{\rm B}) / I_{\rm B} \tag{1}$
108	The net torque acting on the leg L in the direction of the turn is T_F - T and so:

109	$T_F - T = I_L \ddot{\phi}_L$ from which:	
110	$\ddot{\phi}_{\rm L} = (T_{\rm F} - T) / I_{\rm L}$	(2)
111	The angles and angular velocities of B and L $(\phi_B, \dot{\phi}_B \text{ and } \phi_L, \dot{\phi}_L)$ were calc	ulated from
112	the accelerations derived in (1), (2) using stepwise integration.	Q-1
113	A grid search was made for T_{max} between 10 and 30 Nm, T_{min} betw	een –1 and
114	-10 Nm and t_1 between 0.1 and 0.4 s to find the possible time profiles of	T for turns
115	which satisfied all of the following conditions. These were: (a) the leg L	$2 \text{ rotates } 2\pi$
116	radians and stops by the end of the simulation, (b) the body B rotates 2π	radians and
117	the angular velocity of B at the end of the simulation is the same as at the s	start, (c) the
118	foot does not slip more than 0.13 radians in the direction opposite to that of	the turn (as
119	for the experimental data of Imura et al., 2008). The coefficient of friction	$n \mu = 0.2$
120	and time for one turn was 1.0 s. After determining the bounding time	profiles of
121	minimum and maximum T_{max} from the solution space of T, additional	cases were
122	considered in which the friction coefficient ranged from 0.1 to 0.3 ($t_{end} = 1$.	0 s) and the
123	time for one turn ranged from 0.7 to 1.0 s ($\mu = 0.2$), spanning the exp	erimentally
124	determined values of $\mu = 0.2$ and $t_{end} = 0.85$ s.	

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126 **3.** Results

127	For each combination of frictional coefficient μ and turn time t_{end} there were
128	maximum and minimum values for the initial (maximum) value T _{max} of the twisting
129	torque T (Tables 1-4). Each pair of max-min solutions gave rotation angle time
130	histories similar to experimental data and had similar angular velocity time histories
131	(Figs. 4 and 5). For each value of T_{max} lying between the maximum and minimum
132	values there existed unique values of T_{min} and t_{1} for which the body and supporting leg
133	each rotated one revolution and any counter-slipping was less than 0.13 radians as
134	shown in the example (Table 2, Fig. 6). With μ fixed at 0.2, smaller values of t _{end} lead
135	to larger values of minimum T_{max} and consequently to a smaller range of solutions
136	(Table 1). For $t_{end} = 0.76$ there was a narrow range of solutions with T_{max} lying between
137	28.1 Nm and 28.3 Nm and for $t_{end} = 0.75$, or smaller, there were no solutions. For
138	decreasing t_{end} the maximum angle difference ϕ_d between the body and the
139	supporting leg increased (Table 1). The initial angular velocity $\dot{\phi}_{B}$ of the body
140	remained essentially constant for a given t_{end} and was inversely proportional to t_{end}
141	(Table 1).
142	*** insert Table 1 here ***
143	*** insert Table 2 here ***

144 With t_{end} fixed at 1.0 s smaller values of μ lead to smaller values of T_{max} and

145	T_{min} (Table 3). As μ decreased the maximum and minimum values of T_{max},T_{min},and
146	t_1 became closer (Table 3), giving a narrower range of solutions and for μ < 0.12
147	there were no solutions. The initial angular velocity $\dot{\phi}_{B}$ remained essentially constant
148	for the various values of μ .
149	For each solution with given values of μ and t_{end} , there existed solutions with
150	equivalent torque profiles for different combinations of μ and t_{end} . For example if μ
151	increased from 0.20 to 0.25, t_{end} decreased from 1.0 to 0.9 in the equivalent solution
152	(Table 4). The torque profiles of these equivalent solutions have the same t_1/t_{end} values
153	and merely have different scaling factors for torque and time.
154	*** insert Table 3 here ***
155	*** insert Table 4 here ***
156	
157	*** insert Fig. 4 here ***
158	*** insert Fig. 5 here ***
159	4. Discussion
160	The purpose of this study was to determine the possible time history profiles of
161	T for various tempos and friction. For each combination of time of turn and frictional
162	coefficient there is a range of solutions for T (Tables 1-4). The solutions for T satisfy

163	the requirement that the net change in the angular velocity of the body B is zero and
164	that the leg L and body B each rotate 2π at t_{end} . Because the body B rotates under the
165	action of only T, the time integral of T should be zero after one revolution so that there
166	is no net change in angular momentum. The rotation of the leg L is dependent on the
167	net torque T_F - T, so the foot should rotate 2π during slipping as a consequence of
168	sufficient acceleration produced by the net torque. Again the time integral of $T_{\rm F}\mbox{-}\ T$
169	must be zero since the start and end velocities are zero. Hence, T_{max} , T_{min} , and t_1 are
170	such that the integral of T is zero and T_F - T rotates L just one revolution during
171	slipping. For a given value of T_{max} these two constraints give a unique solution for the
172	remaining two degrees of freedom (T _{min} and t ₁). Thus for a given set of conditions (μ ,
173	$t_{end})$ there is a set of torque profiles defined by $T_{max},T_{min},andt_1$ each of which lie
174	within the bounds shown in Tables 1-4. While there is a range of solutions for a given
175	set of conditions (μ , t_{end}), the tight specification of any individual solution may make
176	the Fouetté turn difficult to perform in a steady state since precise timing would be
177	required by the dancer. On the other hand since there are various time histories within
178	the general profiles which produce one revolution of the Fouetté turn (Fig. 6), such
179	time profiles may represent the different styles from different schools.

*** insert Fig. 6 here ***

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181	Initially the twisting torque is positive and less than the limiting frictional
182	torque, accelerating the upper body in the direction of twist while the supporting leg
183	remains stationary with the twisting torque and frictional torque cancelling each other
184	(Figs. 4a and 5a). If the twisting torque exceeds the limiting frictional torque in this
185	phase $(T > 0)$ the foot will slip in the direction opposite to that of the twist. Soon after
186	the upper body starts to decelerate relative to the supporting leg and T becomes
187	negative, the magnitude of T exceeds that of limiting T_F and the foot slips in the
188	direction of twist (Figs. 4a and 5a). Once the magnitude of T falls below that of
189	limiting T _F , the angular velocity of the foot decreases until the foot stops rotating at
190	which time $T = T_F$.
191	For a given coefficient of friction there is a lower bound on the time of the turn
192	since faster turns require larger torques (Table 1) and these are bounded by the limiting
193	frictional torque. This explains why the range of solutions narrows for faster turns
194	(Table 1). There will also be an upper bound on the turn time arising from the assumed
195	time profile of the vertical reaction force N (Fig. 3) since the supporting leg must flex
196	in order to reduce N below one body weight and there is a limit to the amount of
197	flexion possible. The average angular velocity of the body will be inversely
198	proportional to the turn time, and since the angular velocity profiles of the body are

1	0
T	4

199	similar in different solutions (Figs. 4c and 5c) the initial angular velocity $\dot{\phi}_B$ will be
200	approximately inversely proportional to t _{end} (Table 1). Thus if a dancer completes a
201	turn with a net decrease in $\dot{\phi}_{_B}$ this could be compensated for in the next turn by
202	choosing to continue to turn at the new angular velocity and selecting a twisting torque
203	profile with the corresponding t_{end} . Alternatively, a larger T_{max} for the same T_{min} could
204	be used to produce a net gain in angular momentum in the next turn while keeping the
205	same turn time. Real time adjustments for φ_B and φ_L could also be made by
206	modifying the time profiles of I_B and r.
207	As the friction coefficient becomes smaller, the magnitude of T also decreases
208	but so does the range of possible profiles for T so that for a given t_{end} there is a lower
209	limit for μ below which there are no solutions. This is a consequence of not having
210	sufficient $T_F\text{-}T$ to produce the required rotation of the foot. For values of μ below
211	this limit there are solutions with longer turn times since for a given solution there are
212	equivalent solutions with smaller μ and larger t_{end} (Table 4). For larger values of μ ,
213	solutions require larger values of T (Table 3), and so there will be an upper limit on μ
214	imposed by the ability of the dancer to exert large torques. For floors with different μ
215	it will be possible to turn at a given tempo providing μ lies within a certain range.
216	For μ below the lower bound slower turns will be possible and for μ above the

217 upper bound faster turns will be possible up to a limit.

218	For a given pair of values of μ and t_{end} and a particular solution there are
219	other corresponding pairs of values with an equivalent solution for which t_1/t_{end} is the
220	same (Table 4). In comparing these solutions a change of t _{end} by a scaling factor k will
221	correspond to a change in each of \dot{I}_B , $\dot{\phi}_B$, and $\dot{\phi}_L$ by a factor of 1/k and a change in
222	each of $\ddot{\phi}_B$ and $\ddot{\phi}_L$ by a factor $1/k^2$. As a consequence of equations (1) and (2) T and
223	T_F will change by a factor $1/k^2$.
224	There are a number of simplifications associated with the model. The moment
225	of inertia about the longitudinal axis of the supporting leg is assumed to be constant. In
226	an actual performance the knee bends and extends in order to stand on tiptoe and so the
227	moment of inertia will vary. However knee flexion occurs primarily during full foot
228	contact and changing the moment of inertia in this phase would have minimal effect on
229	a simulation since the foot slips very little during this phase. During the majority of the
230	slipping phase the leg is straight and the assumption of constant moment of inertia is
231	reasonable. Although the time profiles of the variables r, I_B , and N are simplifications
232	they were based on the experimental data of a dancer and the calculated leg and body
233	rotation angles were similar to performance data (Figs. 4 and 5). The coefficient of
234	static friction has been assumed to be the same as that of dynamic friction rather than a

235	little larger. The effect of this will have been to reduce the range of possible solutions
236	slightly. The limit of 0.13 radians on foot slippage in the direction opposite to the turn
237	constrains the maximum angle difference between body and support leg to
238	anatomically feasible values of around 1 radian or less in the simulations (Tables 1-4).
239	If this constraint is removed the solution space is much larger but includes simulations
240	with large relative rotations between body and support leg which are beyond
241	anatomical limits.
242	This simple model has been used to describe the solution space of the possible
243	time profiles of the twisting torque T that produce the required rotation about the
244	longitudinal axis in a Fouetté turn. A change of floor to one with increased friction will
245	require a larger twisting torque to turn at the same tempo. A net reduction in the
246	angular velocity of the body B after one turn can be compensated for by increasing
247	T_{max} for the same T_{min} . The model could be applied not only to the Fouetté turn but
248	also to other ballet turns such as the pirouette and Grand Fouetté Italien.
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Т	t _{end}	T _{max}	-T _{min}	t_1/t_{end}	ϕ_{d}	φ _B
max	1.00	28.3	4.9	0.15	0.66	4.49
min	1.00	18.4	5.5	0.23	0.76	4.49
max	0.90	28.3	5.4	0.16	0.68	4.97
min	0.90	20.2	6.0	0.23	0.80	4.97
max	0.80	28.3	6.0	0.18	0.75	5.57
min	0.80	23.9	6.7	0.22	0.91	5.58

Table 1. Ranges of the twisting torque parameters $T_{\text{max}},\,T_{\text{min}},\,t_1$ for which the dancer can turn in steady state ($\mu = 0.2$)

CRIP Notes: ϕ_d is the maximum difference between leg and body angles,

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Table 2. An example of an intermediate twisting torque profile lying between maximum and minimum solutions

_	Т	μ	t _{end}	T _{max}	-T _{min}	t_1	ϕ_{d}	$\dot{\phi}_{\rm B}$
	max	0.30	1.0	42.4	6.5	0.13	0.65	4.52
	int	0.30	1.0	32.3	6.6	0.17	0.65	4.53
	min	0.30	1.0	22.2	8.1	0.27	1.05	4.55

.t body .ody B Notes: ϕ_d is the maximum difference between leg and body angles,

 $\dot{\varphi}_{B}~$ is the initial angular velocity of the body B

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Т	μ	T _{max}	-T _{min}	t_1	ϕ_{d}	$\dot{\phi}_{\rm B}$
max	0.15	21.2	4.2	0.16	0.69	4.46
min	0.15	15.9	4.7	0.23	0.86	4.47
max	0.20	28.3	4.9	0.15	0.66	4.49
min	0.20	18.4	5.5	0.23	0.76	4.49
max	0.25	35.3	5.7	0.14	0.65	4.51
min	0.25	20.1	6.8	0.25	0.89	4.52
max	0.30	42.4	6.5	0.13	0.65	4.52
min	0.30	22.2	8.1	0.27	1.05	4.55

Table 3. Ranges of the twisting torque parameters $T_{\text{max}},\,T_{\text{min}},\,\text{and}\,\,t_1$ for which the dancer can turn in steady state $(t_{end} = 1.0 \text{ s})$

Notes: ϕ_d is the maximum difference between leg and body angles,

 $\dot{\phi}_{B}$ is the initial angular velocity of the body B

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Table 4. Equivalent solutions for twisting torque profiles with different combinations of friction and turn time

Т	μ	tend	T _{max}	-T _{min}	t_1/t_{end}	ϕ_{d}	$\dot{\phi}_{\rm B}$
max	0.20	1.0	28.3	4.9	0.15	0.66	4.49
min	0.20	1.0	18.4	5.5	0.23	0.76	4.49
max	0.25	0.9	35.4	6.2	0.15	0.66	5.02
min	0.25	0.9	22.9	6.8	0.23	0.76	5.02

Notes: ϕ_d is the maximum difference between leg and body angles,

- Fig. 1. Sequential view of one revolution of Fouetté turn. Each picture is shown every 10% time of one revolution (adapted from Imura et al., 2008).
- Fig. 2. The model comprises the supporting leg L and the remainder of the body B. Initial torque directions are shown.
- Fig. 3. Time profiles of (a) radius of the foot contact area, (b) moment inertia of bodyB, (c) normal ground reaction force, and (d) a representative example of the twisting torque T. The abscissae show one time unit for one revolution of the turn and experimental data (normalized to the time of the turn) are shown using dashed lines.
- Fig. 4. Time profiles of a successful Fouetté turn (μ = 0.2) for which the twisting torque parameter T_{max} is minimum: (a) twisting torque (dashed line), frictional torque (thick line), limiting frictional torques (both directions, thin lines), (b) rotation angles of body B (thin line) and leg L (thick line) with experimental data (dashed lines), and (c) angular velocity of body B (thin line) and leg L (thick line).
- Fig. 5. Time profiles of a successful Fouetté turn ($\mu = 0.2$) for which the twisting torque parameter T_{max} is maximum: (a) twisting torque (dashed line), frictional torque (thick line), limiting frictional torques (both directions, thin lines), (b) rotation angles of body B (thin line) and leg L (thick line) with experimental data (dashed lines`), and (c) angular velocity of body B (thin line) and leg L (thick line).
- Fig. 6. An example of an intermediate twisting torque profile (dashed line) between maximum T_{max} (thick line) and minimum T_{max} (thin line) corresponding to Table

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