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**ACTIGRAPHY AND BODY MOVEMENTS IN SLEEP:
EVALUATION, ASSESSMENT AND APPLICABILITY**

by

D. WAYNE DUNHAM, B.A.

A thesis presented to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Arts

Department of Psychology

Carleton University
Ottawa, Canada
April 23rd, 1991.

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submitted by D. Wayne Dunham, B.A.

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Thesis Supervisor

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Carleton University

May 15th, 1991

D3. Mean total accumulated body movement per night for the Side by Limb interaction ($n = 7$)	125
E. Box-Jenkins time series analysis of body movement index for individual actigrams	128

differences were found on any single measure.

The rate of body movement for sleep stages and, separately, for sleep stage shifts, was examined using repeated measures one-way analysis of variance. Movement epochs from the right wrist were transformed ($\ln [x + 1]$) and stage shifts were identified (i.e., 4 epochs of the preshift stage and 8 epochs of the postshift stage). All remaining epochs from sleep onset to morning awakening were sorted into sleep stages. Significant differences revealed an overall trend for declining rate of movement for sleep stages (i.e., WASO > Stage 1 > REM > Stage 2 > SWS). The only pairwise comparison not reaching statistical significance was between Slow Wave (SWS) and Stage 2 sleep.

Movement rate declined with shifts toward deeper sleep and increased with shifts toward lighter sleep. Shifts, back and forth between Stage 2 and REM, showed no significant difference, suggesting a common mechanism for transition between these stages. The comparison between Stage 1 to Stage 2 and Slow Wave to Stage 2 was nonsignificant as well, however, the importance of this finding has yet to be established.

Movement cycles across the night were modeled with Box-Jenkins time series analysis and a significant periodicity of 67.2 minutes was found for the average process. Time series analyses were also performed on individual actigrams and movement cycles between 60.8 and 73.6 minutes accounted for 58% of the recordings. Only four records revealed the expected REM-nonREM periodicity of 89.6 minutes.

Finally, an algorithm for predicting Sleep/Wake *states* (i.e., Sleep = Stage 1, REM, Stage 2, SWS; and Wake = WASO and MT) from BM was developed using stepwise logistic regression. Prospective testing, based on 16 of the 33 records, resulted in a 96.9% epoch-by-epoch agreement between PSG-based and actigraph-based scores. Analysis of the discordant epochs revealed a ratio of 2 : 1 for Wake misscored Sleep versus Sleep misscored Wake. These findings reinforce the notion that the movement-based algorithm fails to predict state when subjects are awake, but motionless.

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General Introduction

"... movement must occur during sleep because the posture on awakening is different from that assumed before sleep."

(MacNish, 1834)

Movement of the somatic musculature was one of the earliest physiological parameters examined in sleep research. Long before the modern era of polysomnography and the discovery of REM sleep, the frequency and magnitude of gross body movements (BMs) were commonly used as measures of sleep quality. We often hear people describe their sleep with phrases like "last night, I slept like a log" or "I tossed and turned all night long". All too often, when commonsense beliefs are tested scientifically, they rarely remain intact in their original form. My examination of the literature addressing BMs in sleep brings into question the simple relationship implied by such aphorisms.

The reason for major postural shifts and minor movements of the body during sleep remains a mystery. One might argue that these movements are in response to muscular discomfort (i.e., an afferent stimulus). This is difficult to support in light of the consistency of movements elicited from night to night (Moses, Lubin, Naitoh, & Johnson, 1972) and the strong relationship between movements and sleep

stages (Aaronson, Rashed, Biber, & Hobson, 1982).

Those interested in phasic arousal mechanisms that operate during sleep (Broughton, 1968; Hunter, 1974), have generally ignored BM as a worthwhile phenomenon of study. This may stem from the view that large BMs appear as artifacts in the polysomnogram (PSG) and traditionally constitute a nuisance to stage scoring. Studies which address the phenomenon of BMs in sleep are scarce and suffer from limitations in technology and research design (cf. Gardner & Grossman, 1975). This has hampered cross-study comparisons and limited the generalization of findings. The present study involves a systematic investigation of the relationship between sleep and BMs elicited during sleep, in an effort to profile and predict the former from the latter.

Literature Review

1. Body Movements in Sleep

1.1 Background

Anecdotal reports of behaviors elicited during sleep can be traced back to the Middle Ages. Nonetheless, it was not until the turn of this century that the scientific study of such phenomena began. Josef Szymanski (1914) invented a device for recording BMs in animals and humans which he called the *sensitive bed*. He also introduced the term

aktogramme to describe the resulting motility record produced by sleeping subjects.

A decade and a half later, H. M. Johnson and T. H. Swan (1930) published a major paper which addressed many of the questions still puzzling researchers in this field. Using the sensitive bed, they described a range of body movements (20 to 60 per night) with an average interval of 11.5 minutes between events. Intrasubject movement reliability was present across consecutive nights of sleep. In contrast, intersubject reliability was lacking (i.e., some subjects were immobile during the first half of the night while others elicited fewer movements during the second half or middle third). Page (1935), using similar technology, replicated the findings and also found that by dividing the temporal course of the *actigram* into thirds, a gradual but significant increase in movements across the night was evident. Laird (1935) saw this as well and termed the trend, the *crescendo effect*.

Research into BMs in sleep waned over the next 20 years and it was not until the modern era of sleep research, ushered in by the work of Nathaniel Kleitman and associates, that interest was rekindled. Aserinsky and Kleitman (1955) noted that eye motility periods (REMPs) were associated with increased BM and that both cycles were concordant with each other. Dement and Kleitman (1957) replicated these observations and by classifying the movements into major and minor types, they proceeded to assess the influence of the movements on the stability of the other sleep stages. Movements occurring during Slow Wave sleep (SWS) were often accompanied by a lightening of the associated

electroencephalogram (EEG). This generalized arousal was then followed by a rapid return to the SWS stage. Major postural shifts in Stage 2 were followed by brief excursions into Stage 1 or wakefulness. Characteristic minor stirrings, jerks, or distal limb movements rarely coincided with these shifts.

The beginning and end of the REM periods were marked by bursts of movement. In addition, subjects elicited very fine, paroxysmal jerks of the limbs, digits, and face during the course of this stage, although they could not be detected as artifact on the electroencephalogram. Movement rate for sleep stages was compared and REM had a lower rate than Stage 2 while SWS had the lowest rate of all.

1.2 *Sleep Stages*

In the 1964 Sakel Lecture to the Society of Biological Psychiatry, Gastaut and Broughton (1965) described ordinary body movements associated with sleep as follows:

Global body movements or, more commonly, the displacement of a part of the body (usually a limb) are very frequent during sleep. They may be associated with EEG changes ranging from a single K complex to an intense awakening reaction, but usually only passage into a lighter phase of sleep is involved. Such body movements are seen in all phases, but are increasingly infrequent as sleep deepens from phase I to IV. The latter, however, is often

ended by a body movement. Movements often precede and end a phase Irem but, apart from the partial myoclonic jerks [already described], are relatively rare during this phase. Sleep cycles are usually terminated by a body movement, and such movements become more frequent as the cycles pass and as sleep globally becomes lighter. (p. 199)

Studies conducted over the past two decades have generally confirmed their clinical observations. Sassin and Johnson (1968) electromyographically (EMG) monitored 5 subjects for two consecutive nights and recorded rate and distribution of movements for sleep stages. Stage 1 had the highest frequency (0.42 movements per minute) and the movements were evenly distributed across the stage duration. REM sleep had a lower rate (0.20 per minute) and was characterized by small, distal jerks, again, evenly distributed across the holding time. Stage 2 followed REM (0.17 per minute), but these stages did not differ statistically. Slow Wave sleep had the lowest rate (0.06 per minute) and over 80% of the movement occurred as global postural shifts, invariably clustered at the end of this stage. Naitoh, Muzet, Johnson and Moses (1973) confirmed their results for REM (0.20 per minute) and Stage 2 (0.16 per minute).

Azumi, Shirakawa and Takahashi (1977) found contradictory evidence. They recorded 8 subjects over seven nights with a sensitive bed apparatus. Movement rates declined from REM (0.16 per minute), to Stage 1 (0.07 per minute), to Stage 2 (0.05 per minute), to SWS (0.01 per minute). The temporal distribution of the REM periods revealed a

gradual increase in major and minor BMs that was not evident in the corresponding nonREM sleep.

Jukka Alihanka (1982) studied BM types defined by duration using the *static-charge* sensitive bed and his findings were in agreement with those of Sassin and Johnson (1968) and Naitoh et al. (1973). Slow wave sleep was described as a long motionless period terminated by major postural shifts. The frequency of all BM types was lowest during this sleep stage. REM was characterized by twitches or tremors of the face and extremities. Their form, number, and duration were highly variable and they occurred in brief trains separated by short intervals – a pattern distinct from any other stage. REM sleep was also characterized by larger distal movements that rarely involved global postural shifts. Wakefulness after sleep onset (WASO) was distinguished by large postural shifts and movements of all types. Stage 1 registered fewer movements than WASO but the enormous variance inherent to these stages prevented statistical comparisons. Both stages were short in duration and the limited samples may have been misrepresentative, as well. Contrary to previous research, the movement rate for REM was not statistically different from either WASO or Stage 1.

Wilde-Frenz and Schulz (1983) also reported overlapping movement distributions for WASO and Stage 1. REM did have significantly fewer movements than either of these stages. However, the order of declining movement rates became less certain when single nights were ranked. Pollmaecher and Schulz (1987), using wrist actigraphs, demonstrated a marked separation in movement rate for individual sleep

stages. Rates declined from WASO to Stage 1 to REM to Stage 2 to Slow Wave sleep. Wake and Stage 1 were characterized by high movement counts early into the stage followed by a gradual decline across the remaining duration. Stage 2 displayed a weak positive trend towards elevated movement while REM showed an even distribution across the holding time. Slow Wave sleep was characterized by a *floor effect* for movement count.

Clearly, movement rates differ for individual sleep stages. Nevertheless, the hierarchical ordering of these stages seems less certain, particularly for the lighter stages of sleep (Stage 1 and REM). This ambiguity may be a reflection of the diverse methodologies and analyses used.

1.3 Stage Shifts

Muzet, Naitoh, Townshend and Johnson (1972), using the EEG artifact technique, recorded 10 subjects over nine consecutive nights. They limited their analysis to four transitions: (a) Stage 2 to SWS; (b) Stage 2 to REM; (c) SWS to Stage 2; and (d) REM to Stage 2. Movement frequency per 10 minutes of Stage 2, immediately preceding or following the transition, was the dependent measure. Intervals between the last movement in Stage 2 and onset of SWS or REM sleep were also examined.

Of all the 10 minute epochs preceding SWS, 86% were motionless

and the remaining 14% never exceeded two movements. This pattern was common to both nocturnal Slow Wave periods. The Stage 2 epoch following SWS was exactly the opposite. It was characterized by major movements (i.e., 17 epochs had counts of five or more). Transitions from Stage 2 to SWS were uneventful as shown by movement intervals of greater than 5 minutes between stages.

Unlike SWS, only 20% of the 10 minute epochs preceding REM were movement-free and the other 80% rarely exceeded three movements. The post-REM epoch had a lower movement rate in comparison but this difference was not significant. Again, contrary to SWS, the average interval between the last movement in Stage 2 and REM onset was less than 5 minutes. Muzet and colleagues concluded that BMs were incompatible with transitions from Stage 2 to SWS and did not interfere with similar transitions into REM.

Alihanka (1982) noted that 31% of all the stage shifts that he categorized were associated with body movement. This was twice the rate reported by Sassin and Johnson (1968). He examined a broader range of transitions and grouped them into ascending and descending types. Of all the movement epochs observed, 10% involved transitions from wakefulness to sleep. Transitions, back and forth, between Stage 2 and SWS or REM sleep were similar to those described by Muzet et al. (1972). Alihanka also noted high movement rates associated with shifts from Stage 2 and REM to Stage 1, and Stage 1 to Wake.

Aaronson et al. (1982) using time-lapse photography, studied 4 subjects over as many nights. Sleep onset was characterized by a large,

single movement or a series of smaller, rapid movements. This was followed by a period of relative immobility coincident with Slow Wave sleep. Two or more major BMs separated this period from a second span of immobility (i.e., the second nocturnal Slow Wave phase). These two distinct episodes of immobility were followed by a series of short movement-free periods spaced evenly across the remaining night. The researchers concluded that the occurrence of movements was confined to specific points in the sleep cycle (i.e., the end of the descending nonREM and REM phases). Seven or eight key phase shifts across the night were detailed and 85% were associated with major body movements. Interestingly, transitional shifts out of nonREM and REM sleep accounted for only 4% of a night's sleep.

Stage shift analyses have generally complimented the work involving sleep stages and body movement. A consensus for shifts into Stage 2 and SWS being relatively movement-free, has been established. It seems equally true that shifts out of these stages are accompanied by major postural movements. Shifts into and out of REM are characterized by bursts of small movements. The overall scheme describes stage shifts toward sleep descent as concomitant with a decline in minor body movement frequency. During sleep ascent, stage shifts are associated with isolated episodes of major BMs which gradually decrease in frequency the closer the sleeper approaches wakefulness.

1.4 *Movement Cycle*

Jovanovic (1971) looked at the distribution of movements within and across multiple sleep periods. The first typical period averaged 140 minutes and accounted for 22% of the movements recorded. The majority of these movements were clustered in the initial 10 minutes of the period and declined sharply, thereafter. The second period was 100 minutes long and mirrored the first with respect to the BM profile. On average, this cycle accounted for 21% of the movement detected. Period 3 (110 min) and 4 (140 min) contained 20% and 18% of the night's movements, respectively, and paralleled the previous two cycles. The fifth period was only 50 minutes long but accounted for 19% of the total movement. Most of this activity was clustered in the last 10 minutes of the cycle.

Schulz and Dirlich (1973), using a sensitive bed apparatus, recorded movement counts from 5 subjects over 28 nights. Reduced to 5 minute epoches, the data were analyzed with time series autocorrelation. They found a robust movement cycle oscillating approximately every 100 minutes in-phase with the REM-nonREM cycle. Similar observations have been reported elsewhere (Alihanka & Hasan, 1979; Alihanka, 1982; Aaronson et al., 1982).

1.5 *Body Laterality*

Muller-Limmroth (1965) was the first to note a curious propensity

for right-handers to move their left arms while asleep:

Tickling the nose causes right-handed people to make a defensive movement with the left hand. Evidently the depth of sleep is not the same in the two hemispheres. Dominance of one hemisphere means that body movements tend to be made on the corresponding side, and hence there is a greater activation of the motor and sensory regions of the brain. This also results in 'deeper sleep' in these regions of the brain. (p. 22)

Uros Jovanovic (1971) studied the phenomenon of laterality of movements in sleep, using the EMG technique. He determined that 70% of all unilateral movements registered in the course of a night came from the left arm of right-handed subjects. Minor BMs were far more sensitive in showing this difference and the nondominant movement bias was present in both REM and nonREM sleep. In a case study of a right-handed subject, recorded over six nights, Gardner and Grossman (1975) observed twice as many unilateral movements in the nondominant arm.

Although I could find no report in the literature dealing specifically with the issue of limb differentiation, Jovanovic (1971) did note that the arm and leg of the sleeping subject were equally sensitive in revealing lateral differences. This statement is somewhat ambiguous in light of the fact that it is confounded by the issue of laterality (i.e., one is not certain if the two limbs differed in terms of absolute movement).

1.6 *First Night Effect*

Several investigators have reported that sleep and dreams are atypical on the first night spent in a laboratory setting (Agnew, Webb, & Williams, 1966; Mendels & Hawkins, 1967; Browman & Cartwright, 1980). This phenomenon has been termed the *first night effect*. Although this literature has primarily concerned itself with the traditional PSG variables (e.g., total sleep time and sleep efficiency), body movements have not been ignored. Sassin and Johnson (1968) reported significantly more movements during Stage 1 on the first night compared to a second night. No differences in gross motility were noted between nights for REM, Stage 2, or Slow Wave sleep.

Jovanovic (1971) found an interaction between the first night effect and laterality of movements for REM. Unilateral BMs tended to be more evenly distributed between the upper limbs in right-handed participants on the first night. In contrast, significantly fewer movements were detected on the second night in the laboratory. He also reported a significant increase in REM-specific paroxysmal jerks on the first night.

Azumi et al. (1977) found no significant differences in minor BMs across four consecutive nights of recording. There were significantly fewer major movements during the first and second as compared to the third and fourth nights. Shirakawa and Azumi (1979) confirmed these results and concluded that no first night effect was present as measured by the interval between movements or rate of movements for stage shifts.

1.7 Reliability

Moses et al. (1972) reported significant intercorrelations between nights for Movement time ($r = 0.45$) and movement frequency ($r = 0.62$). They concluded that the number of large postural shifts, representative of Movement time (MT), was stable from one night to the next.

Gardner and Grossman (1975) looked at the course of BMs in Stage 2 sleep across two consecutive nights and reported a significant correlation ($r = 0.70$) for movement rate. Wilde-Frenz and Schulz (1983) replicated this finding and found that the reliability of movement rate improved as a function of the number of nights sampled.

Although a number of broad generalizations, such as those originally presented by Gastaut and Broughton (1965), have been substantiated, attempts to detail these observations have resulted in equivocal findings. This ambiguity stems from the eclecticism demonstrated in the research (i.e., a variety of techniques and apparatus have been utilized but have rarely been cross referenced). Even if a single method were agreed upon, technological advances would serve to constantly redefine the parameters and render previous work doubtful. Other barriers include the lack of consensus over operationalizing variables, the importance of the variables, and how these variables should be analyzed. A common methodology and state-of-the-art technology are needed if important contributions to our understanding of the significance

of BMs in sleep are going to be made.

2. *Actigraphy and Sleep*

Generically speaking, the term *actigraphy* is synonymous with the recording of movement (e.g., sensitive bed, EEG artifact, EMG, photography, and direct observation). Notwithstanding, the term has become exclusive to movement-sensitive transducers which can be attached to the body. Prototypes of the actigraph included a variety of semiconductor strain gauges which could be applied to a number of body locales (Baldrige, Roy, Whitman, & Kramer, 1965). These devices evolved into the self-contained, digital, activity counters of today (Redmond & Hegge, 1985).

Kripke, Mullaney, Messin, and Wyborney (1978) published the first account of actigraphy being used to predict Sleep/Wake *states* as established by concomitant polysomnography. They used an analogue forerunner of the modern actigraph to monitor 5 subjects and the resulting actigrams were scored visually for Wake and Sleep using a "best guess" approach. The PSGs were scored for Wake (i.e., WASO and MT) and Sleep (i.e., Stage 1, Stage 2, SWS, and REM), and several cumulative measures including total sleep period (TSP), total sleep time (TST), and WASO were correlated between the two methods. The coefficients obtained were all highly significant ($r = 0.95, 0.98, \text{ and } 0.85$, respectively).

Again, Kripke and associates tested the viability of the actigraph to

predict Sleep and Wake states (Mullaney, Kripke, & Messin, 1980). Sixty-three subjects were recorded and the scoring criteria for the actigram were documented (i.e., if 50% or more of the 30 second epoch was active, it was scored Wake, otherwise, it was scored Sleep). Context was also accounted for (i.e., if an epoch was initially scored Sleep, the two adjacent epoches were checked for compliance). The resulting correlation coefficients for TSP, TST, and WASO were remarkably similar to those reported earlier. Epoch-by-epoch agreement was 96.3% and a subsequent breakdown of the discordant epoches revealed three times as many false positives (i.e., Wake misscored Sleep) as false negatives (i.e., Sleep misscored Wake). The researchers found that the actigraph tended to overestimate the TST by 15 minutes. They reasoned that this discrepancy was due to wakefulness without motion; probably occurring prior to sleep onset or after morning awakening.

Since sleep onset was singled out as the most likely source of the false positives, an evaluation of sleep onset estimation was performed. It was determined that 55% of the onsets were overestimated while 32% were underestimated. On average, the actigraph was 4.2 minutes premature in predicting sleep onset.

A third study in this series was conducted with a digital actigraph (Webster, Kripke, Messin, Mullaney, & Wyborney, 1982). In the first experiment, 20 subjects were monitored for sleep and body movements. One minute epoches of EEG were scored Wake or Sleep and a computer was programmed to determine an algorithm, based on 17 of the records, for predicting Sleep/Wake states.

The resulting equation was:

$$D = .025 [0.15 T (i - 4) + 0.15 T (i - 3) + 0.15 T (i - 2) + \\ 0.08 T (i - 1) + 0.21 T (i) + 0.12 T (i + 1) + 0.13 T (i + 2)]$$

If D was greater than or equal to one, the movement-based epoch was scored Wake, otherwise, it was scored Sleep. Epoch-by-epoch agreement was 94.5% and a prospective test, based on the three remaining records, produced 96.0% concordance. Again, all of the misscored epoches were examined and false positives outweighed false negatives. A supplementary set of rules were drawn up to improve the accuracy and the level of disagreement dropped from 5.5 to 5.3 percent. When the data were expressed in terms of TST, only 0.8% of the overall record was overestimated, accounting for only 4.4 minutes of misscored sleep.

In the second experiment, they recorded 28 subjects, and design modifications to the actigraph warranted generation of a new algorithm:

$$D = .036 [0.07 T (i - 5) + 0.08 T (i - 4) + 0.10 T (i - 3) + \\ 0.11 T (i - 2) + 0.12 T (i - 1) + 0.14 T (i) + 0.09 T (i + 1) + \\ 0.09 T (i + 2) + 0.09 T (i + 3) + 0.10 T (i + 4)]$$

Based on 14 records, retrospectively-determined reliability was 93.9% while the prospective test, based on the other 14 records, resulted in an epoch-by-epoch agreement of 93.0%. With respect to the TST, the

retrospective and prospective correlation coefficients were identical ($r = 0.97$). Again, the actigraph overestimated sleep when subjects were actually awake (i.e., 5.6 min, retrospectively and 6.5 min, prospectively).

Cole and Kripke (1988) employed a state-of-the-art digital actigraph to record wrist movements in 6 normal sleepers. Again, EEG was scored in 1 minute epoches of Wake or Sleep. Actigraphic counts were collected in 2 second epoches and an equation was derived by multiple linear regression as follows:

$$S = 1.004 + [-0.001(i - 5) + -0.001(i - 4) + -0.001(i - 3) + -0.001(i - 2) + -0.003(i - 1) + -0.007(i) + -0.001(i + 1) + -0.001(i + 2)]$$

If S was less than or equal to 0.5, the 1 minute epoch was scored Wake, otherwise, it was scored Sleep. Epoch-by-epoch reliability was 91.7%. Unfortunately, the equation was not tested prospectively.

Newman, Stampi, Dunham, and Broughton (1988) also used digital actigraphs to monitor the activity of 4 normal sleepers over 24 hours. Movement counts were collected in 20 second epoches and a *sliding window* was used to classify them as Sleep or Wake. Basically, if three successive epoches each had 20 counts or less, the first epoch was scored Sleep – any other combination resulted in a score of Wake. The correlation coefficient between the PSG-based and actigraph-based TST was 0.91, and the actigraph overestimated sleep by 3.6 minutes.

It is obvious from the small number of publications reviewed, that the scientific study of BMs using actigraphs is still in its infancy. The device's technological evolution has been rapid compared to other movement-detecting apparatus, and this has resulted in a remarkably sensitive machine capable of registering positional displacements as minute as 0.01 g.

Attempts to predict Sleep and Wake from movement seem to have plateaued. Correlations and other indices of reliability have been consistently high but this is not surprising when one considers that sleep is a relatively immobile state. One reason for this slow down may be the excessive time and effort put into developing mathematical algorithms that can discriminate between Sleep and Wake (Webster et al., 1983; Cole & Kripke, 1988). Simpler heuristics may produce comparable results with much less effort (Newman et al., 1988).

Several drawbacks have hindered efforts to predict Sleep/Wake states from motility records. Aside from the technological shortcomings of earlier versions, time synchronization between the PSG and the actigraph has not been satisfactorily achieved. Another source of error is the traditional referent, the polysomnogram, which is far from exact with respect to data reduction and algorithm development. Other factors such as body laterality, first night effect and limb differentiation may be influencing the success of these prediction exercises as well.

The Current Experiment

This study was designed to explore the relationship between sleep and concomitant body movement. The principal objective was to profile and ultimately predict the former from the latter. Specifically, a number of parameters suspected of influencing BMs during sleep were considered (i.e., *first night effect*, body laterality, and limb differentiation). Intra- and intersubject reliability, measured between nights and between subjects, respectively, were also assessed. In addition, the study was comprised of separate analyses of BMs in sleep stages and stage shifts, which served to facilitate the development and testing of a movement-based Sleep/Wake staging algorithm.

Experimental Hypotheses

Overnight PSGs were collected at home using ambulant actigraphic and electrographic apparatus. Data were reduced to 32 second epochs, anchored to sleep onset (i.e., the beginning of the first 3 min of continuous Stage 2 sleep), and a variety of statistical routines, including analysis of variance (ANOVA), bivariate correlation, Box-Jenkins time series analysis (ARIMA), and stepwise logistic regression, were used to help summarize and interpret the data.

Based on the literature review presented earlier, a number of formal hypotheses were tested. First, if an unfamiliar sleeping environment (e.g., a sleep laboratory) adversely affects the quality and

quantity of sleep on the initial night (first night effect) then subjects sleeping in familiar surroundings (e.g., one's own bed or bedroom) should not experience disturbances of this nature. Three consecutive nights of at-home recordings should be sufficient to demonstrate any possible differences in either BM or traditional PSG parameters between nights.

Secondly, the placement of actigraphs on both wrists and ankles will allow for an assessment of the possible differences in rate of movement between the left and right sides of the body, and between the arms and legs. Body laterality and limb differentiation remain relatively unexplored but several observations suggest that the nondominant limb is more active during sleep and that the wrist and ankle move with equal magnitude.

Thirdly, if lighter stages of sleep (e.g., REM) are characterized by lower thresholds for arousal (Sassin & Johnson, 1968), it follows that movement rates for these stages will be greater than for deeper stages (e.g., SWS). Individual stages should be differentiated along a trend for declining rate of movement as follows: WASO > Stage 1 > REM > Stage 2 > Slow Wave sleep.

Fourthly, average movement rates for clearly defined stage transitions are also sensitive measures of arousal state (Muzet et al., 1972). A substantial portion of the gross amount of movement in sleep occurs during stage transitions and thus, differential movement rates may be capable of defining particular stage shifts. If the implied relationship between arousal threshold and BMs is reasonable then stage shifts toward deeper sleep (e.g., Stage 2 to SWS) should be characterized by less

movement while shifts toward lighter sleep (e.g., SWS to Stage 2) should coincide with more movement.

The remaining topics are not as easily addressed by formal scientific hypotheses, however, the following questions asked are no less important and are just as valid. Body movements and sleep are temporal phenomena and as such, are subject to study within the time series domain. Oscillations in movement amplitude require examination and several basic questions addressed here, include: (a) Does BM, tracked across the night, show a periodicity, and if so, (b) is it consistent with the 90 minute REM-nonREM cycle of sleep? Furthermore, are there relationships between BM and separate sleep stages expressed as a function of time?

Other questions related to the temporal nature of BMs and sleep involve reliability between nights (intrasubject) and between subjects (intersubject). More specifically: (a) Does an individual move during sleep at roughly the same point in his or her sleep cycle from night to night, and (b) do people move at roughly the same time relative to sleep onset on any given night? All of these questions can be asked of sleep structure as well as body movement.

Finally, if the relationship between sleep and BM is robust with respect to time, then movement may be a powerful predictor of the Sleep/Wake *state*. This relationship can be expressed as a stochastic function which is easily assessed for reliability. The outcome of such an assessment may have practical implications for an automated scoring routine.

METHOD

Subjects

Eleven normal sleepers (i.e., 6 females and 5 males), 19 to 31 years of age ($M = 25.9$, [$SD = 4.0$]), were recruited and received \$30.00 each, for participating. The Edinburgh Handedness Inventory (Oldfield, 1971) was used to select subjects with a strong right-hand preference (see **appendix A**). The mean quotient for right-handedness was 0.95 , ($SD = 0.06$). Subjects also underwent a personal interview and completed a sleep history questionnaire (see **appendix B**). The most important subject selection criteria were as follows: Subjects had to (a) be right-handed; (b) be nonnappers; (c) have a normal sleep duration (6 to 8 hours); (d) have no long-term sleep complaints; and (e) be drug-free.

Participants were briefed on the nature and purpose of the experiment and signed consent was obtained (see **appendix C**). Subjects were requested to abstain from coffee, tea, cola, alcohol, strenuous exercise, and excess eating for at least 6 hours prior to their individual normal bedtime.

Apparatus

Each subject underwent three consecutive weeknights, beginning on either a Monday or a Tuesday, of ambulant polysomnographic recording at home. Electrographic data were collected with a Medilog MR-90-B physiological recorder (Oxford Medical Inc.). This device is similar to a

small, battery-driven, personal tape recorder ($15 \times 12 \times 3 \text{ cm}^3$) and stores eight analogue physiological signals on a 120 minute audio cassette. Tapes were replayed on a Medilog 9000 playback unit in 16 second screens for visual scoring. Body movement was recorded with an actigraph activity monitor (Ambulatory Monitoring Inc.). The actigraph is a small, self-contained unit ($6.5 \times 4.0 \times 1.5 \text{ cm}^3$) housing a piezotransducer and a computerized digital microprocessor (Redmond & Hegge, 1985). The device interfaces with a computer during initialization and "download" procedures.

Procedure

Subjects arrived at the laboratory [Human Neurosciences Research Unit - University of Ottawa] sometime between 20:30 and 22:00 hours. Time of arrival was agreed to so as not to jeopardize the subject's normal bedtime routine. Gold-cup electrodes were secured to the scalp using collodion or were taped to the skin. The montage included two EEG leads: C_4 and C_3 referenced to contralateral mastoids (M_1 and M_2 , respectively); two EOG leads: right outer canthus and left outer canthus, again, referenced to contralateral mastoids; submental EMG; and right and left anterior tibiae which were recorded only during the first night. Ground leads were fixed to C_z and O_z . All scalp placements were made according to the *International 10 - 20 System* (Jasper, 1958). The anterior tibiae were included as a clinical screen for periodic leg movements in sleep (PLMS), a pathophysiological disorder characterized by stereotyped, repetitive movements of the lower extremities (Coleman,

Pollak, & Weitzman, 1980).

Electroencephalographic and EOG channels were calibrated at 100 μ V peak to peak while EMG channels were calibrated at 25 μ V peak to peak. Skin impedance for all electrodes was below 5 K Ω at the time of application.

Four actigraphs were initialized with a digital IBM computer and synchronized with the LCD clock of the Medilog recorder. The actigraphs were programmed to record movement in 2 second epoches and were then strapped to the wrists and ankles. Electrodes were plugged into the Medilog and the subject was given written instructions concerning several tasks that he or she would be required to execute before and after the recording. These tasks involved: (a) switching on the Medilog , 5 minutes before "lights out", and switching it off, 5 minutes after morning awakening; and (b) pushing the Medilog's marker event button at lights out and at morning awakening. The participant also received a kit with supplies for removing the electrodes. When the hookup was complete, the subject was driven home and arrangements were made to pick up the equipment the next day.

Data Analysis

Thirty-three Medilog cassette tapes (TDK D120) and corresponding actigraph data files were coded "blind" with respect to subject and night. Polysomnographic data were scored visually, on-screen, with a Medilog 9000 replay/display unit, in 16 second epoches according to Rechtschaffen and Kales (1968). Sleep stages were then reduced to

32 second epoches, after the fact.

Conventional sleep measures, such as TST; % WASO, % Stage 1, % Stage 2, % SWS (Stage 3 & 4), % REM, and % Movement time (MT); latencies to sleep onset, SWS and REM; and the sleep efficiency index, were determined. Interrater reliability (87%) was based on an epoch-by-epoch comparison of three complete recordings.

Two second actigraph epoches were reduced to 32 seconds by simple summation. Both sleep and corresponding actigraph epoches were anchored to the appearance of the first *K-complex* or *spindle* in the PSG record. This event was considered sleep onset if it signaled the beginning of the first 3 minutes of continuous Stage 2 sleep. Thus, 32 second sleep and BM epoches were the raw measures for all subsequent data reduction exercises.

The first set of hypotheses, associated with BM and the *first night effect*, body laterality, and limb differences were addressed within a 3 x 2 x 2 (Night by Side by Limb) completely within-subjects factorial design. The dependent measure was the total accumulated movement count per recording. Average epoch count was not considered because of its probable bias against finding differences between nights. Repeated measures ANOVA was used and, when appropriate, corrected *F* tests based on the modified Geisser-Greenhouse procedure were reported (Dixon, Brown, Engelman, & Jennrich, 1990). Post hoc simple main effects analysis was used to detail interactions (Kirk, 1982). Comparisons between nights were also performed with repeated measures one-way ANOVA on conventional sleep parameters.

All subsequent analyses were based on transformed movement data

($\ln [x+1]$) from the right wrist. The reasons for choosing this particular transformation and movement site are discussed in **appendix D**.

Intrasubject (between nights) and intersubject reliability were assessed on a number of dependent measures with several techniques. Sleep and movement epoches were further reduced to 4.8 minutes (9 epoches) and data matrices for three nights and 11 subjects were established. This epoch length (4.8 minutes) was chosen with the understanding that a wider sample window would *smooth* the temporal process and enhance the strength of any possible association between the variables. In addition, computer memory was insufficient for performing data analyses on the 32 second epoches. This limitation also influenced my decision to collapse the data, resulting in a reduced number of epoches.

Pearson product-moment correlations (r_{xy}), Kendall's rank order correlations (r_{τ}), percent epoch concordance, and composite measures such as the estimated common intravariability correlation (ECIC) and Cronbach's α were utilized (Norusis & SPSS Inc., 1988). Conventional sleep parameters were also assessed for reliability between nights using Pearson product-moment correlations.

The search for a sleep-based movement cycle was conducted with time series procedures. Raw 32 second movement epoches were reduced to 3.2 minutes (6 epoches) and sleep stages were converted to 3.2 minute percentage epoches. The decision to reduce the data from 32 second epoches to 3.2 minute epoches was based on similar arguments presented above, with reference to the reliability analysis. Because the time series data sets were smaller than the reliability matrices, more computer memory was available for the data reduction process. As a result, more

epoches could be generated and the resolution of the process was improved (i.e., 3.2 min vs. 4.8 min epoches). Box-Jenkins time series analysis (Box & Jenkins, 1976) was performed on the 33 individual actigrams as well as the averaged process in order to model the data and detect rhythmical movement patterns. Polynomial regression was performed on the average process as an alternative curve-fitting technique (Pedhauzer, 1982). The five sleep stage processes (i.e., %WASO, %Stage 1, %REM, %Stage 2, and %SWS) were also modeled with Box-Jenkins time series and polynomial regression algorithms. After acceptable models had been fitted to the averaged actigram and percent sleep stage processes, the residual error time series were examined. Cross-correlations between the averaged actigram and the percent sleep stage processes were performed in order to show possible phase relationships. Once adjustments for phase alignment were made to the series, stepwise multiple regression of the percent sleep stages on the BM index was performed as a means of assessing the time dependent relationships between these variables.

The second set of formal hypotheses, associated with BM and sleep stages – stage shifts, were tested with separate within-subjects one-way analysis of variance. The dependent measure was average movement rate. Each actigram was sorted for five principal stage shifts: (a) Stage 2 - SWS ; (b) Stage 2 - REM ; (c) REM - Stage 2 ; (d) Stage 1 - Stage 2 ; and (e) SWS - Stage 2. The sample window included four 32 second preshift epoches and eight postshift epoches. After the stage shift epoches were removed, the remaining record was sorted into stages: (a) SWS ; (b) Stage 2 ; (c) REM ; (d) Stage 1 ; and

(e) WASO. Care was taken to preserve shift and stage processes for eventual time-dependent modeling. Adjusted Geisser-Greenhouse F tests were reported (Dixon et al., 1990) and post hoc analyses were conducted using Newman-Keuls pairwise comparisons procedure (Kirk, 1982). Acceptable stage shift and sleep stage processes were averaged and polynomial curves were fitted in an effort to better characterize the temporal distribution of these stage-dependent BM series.

The last major objective of this study was to quantify the relationship between BM and Sleep/Wake *states*. The principal sleep stages were recoded into Sleep (Stage 1, Stage 2, REM, and SWS) and Wake (WASO and MT), and 17 records were chosen randomly as the data source for building the prediction algorithm (i.e., the retrospective sample). By shifting the actigram to a maximum of 10 epoches prior to and 5 epoches after the actual event, 16 predictor variables were regressed on the binary Sleep/Wake codes with stepwise logistic regression (Dixon et al., 1990). The resulting constant and the variable coefficients were then applied to a set of corresponding actigram variables from the remaining 16 records (i.e., the prospective sample). Each record was staged (Sleep or Wake) with the prediction algorithm and epoch-by-epoch comparisons were drawn between the PSG-standard score and the movement-based prediction score. Total durations for Sleep and Wake per record were compiled and dependent t tests were used to detect differences. Pearson product-moment correlations between respective variables were also obtained in order to assess the degree of reliability inherent in the algorithm. All tests of significance, whether for mean differences or *goodness-of-fit*, were two-tailed.

RESULTS

Movement Parameters

Average real clock time for lights out was 23:36 hours ($SD = 45$ min) and mean sleep onset was at 24:00 hours ($SD = 47$ min). Morning awakening occurred, on average, at 07:03 hours ($SD = 43$ min). The mean sleep latency was 23 min ($SD = 14$ min) and sleep duration averaged 423 minutes ($SD = 59$ min). Synchronization of apparatus with respect to clock time was critical to the success of this experiment and after careful examination of the raw data, I was convinced that this objective had been met. Figure 1 shows that large body movement counts displayed in the lower half of each composite hypnogram/actigram are concomitant with ascending stage shifts into wakefulness and Stage 1, shown in the upper half of each illustration. The very close alignment of the polysomnogram-based MT markers with the largest BM counts also adds to the evidence that a high degree of synchronization was achieved.

1. First Night Effect, Laterality, Limb Differentiation

Before reporting the results from this part of the study, it is important to note that the data were compromised by five distinct incidents of equipment failure. Specifically, 5 of the 132 actigrams collected, contained brief periods of suspicious looking raw data. The movement counts were unusually high and did not correspond with the

Figure 1. HYPNOGRAM-ACTIGRAM. Sleep hypnogram and movement-based actigram (right wrist) of Subject no. 6 on Night 1, 2, and 3.

other three matched recording sites. For example, the left wrist actigraph of Subject 6 (L.M.) on Night 1 recorded a 34 minute series of elevated counts during a SWS period. These counts were consistently large, nonvarying, and atypical of the three corresponding actigraphs at the other sites, which recorded little or no activity during this period. This anomaly reoccurred on four other occasions (i.e., three more times at the left wrist and once at the left ankle). Unfortunately, the questionable recordings involved 4 subjects and the rigid requirements of the within-subjects design (i.e., balanced data for all cells) warranted replacing the five values with predicted data generated by *maximum likelihood estimation* algorithms (see **appendix D**).

From the 3 x 2 x 2 (Night by Side by Limb) completely within-subjects ANOVA performed on the total accumulated movement index, only the Side by Limb interaction was significant, $F(1, 10) = 8.28$, $p < .05$ (see **Table 1a**). Simple main effects tests associated with this interaction are shown in **Table 1b**. Two tests were significant: (a) Side at wrist, $F(1, 10) = 16.53$, $p < .01$; and (b) Limb at left, $F(1, 10) = 6.92$, $p < .05$. The left wrist ($M = 4797.6$) was more active than either the right wrist ($M = 4249.4$) or the left ankle ($M = 3860.6$) as shown in **Table 1c**. No differences were found between nights; between the left and right side of the body; or between the wrist and ankle.

One-way, repeated measures ANOVAs were performed on conventional sleep measures derived from the PSG and none of these tests proved significant for differences between nights (see **Table 2**). It is apparent that sleep and BM recordings obtained with ambulant equipment in normal surroundings do not induce the first night effect.

Table 1a

Analysis of variance of total accumulated body movement per night comparing wrists and ankles on the left and right sides of the body between three consecutive weeknights of sleep.

<i>Source of Variance</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>
A (Nights)	275.46	2	137.73	0.70
A(error)	3924.27	20	196.21	
B (Side)	2.61	1	2.61	0.36
B(error)	72.25	10	7.22	
C (Limb)	75.33	1	75.33	4.34
C(error)	173.69	10	17.37	
AxB	7.00	2	3.50	0.79
[AB](error)	88.33	20	4.42	
AxC	3.64	2	1.82	0.42
[AC](error)	86.23	20	4.31	
BxC ^a	69.58	1	69.58	8.28*
[BC](error)	84.00	10	8.40	
AxBxC	10.61	2	5.31	1.37
[ABC](error)	77.66	20	3.88	

Note. To facilitate comprehension, the sums of squares and mean squares are multiplied by the constant, 10^{-5} .

^a Simple main effects analysis of the Side by Limb interaction is presented in Table 1b.

* $p < .05$

Table 1b

Simple main effects analysis of variance of total accumulated body movement per night for the Side by Limb interaction.

<i>Source of Variance</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>
<u>B (Side) at C (Limb)</u>				
B at c ₁ (wrist)	49.58	1	49.58	16.53**
B at c ₁ (error)	29.99	10	3.00	
B at c ₂ (ankle)	22.61	1	22.61	1.79
B at c ₂ (error)	126.25	10	12.63	
<u>C (Limb) at B (Side)</u>				
C at b ₁ (left)	144.85	1	144.85	6.92*
C at b ₁ (error)	209.19	10	20.92	
C at b ₂ (right)	0.06	1	0.06	0.01
C at b ₂ (error)	48.51	10	4.85	

Note. To facilitate comprehension, the sums of squares and mean squares are multiplied by the constant, 10^{-5} .

Means are presented in Table 1c.

* $p < .05$

** $p < .01$

Table 1c

Mean total accumulated body movement per night for the Side by Limb interaction.

Side	Limb			
	Wrist		Ankle	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Left	4797.6 ^a	2966.8	3860.6	2662.1
Right	4249.4	2760.8	4230.8	2768.5
^a <i>n</i> = 33 observations.				

Table 2

Comparisons between three consecutive weeknights for traditional sleep parameters.

Variable	Night 1		Night 2		Night 3		<i>df</i> (error)	<i>F</i> ^a
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
TST + Stage 1 (min)	432.5	68.2	419.8	63.3	408.7	49.5	18 ^b	1.11
Sleep efficiency (%)	95.8	2.0	94.9	4.2	95.2	2.6	"	0.40
WASO/MT	"	4.3	1.9	4.3	4.7	2.5	"	0.40
Stage 1	"	8.3	3.1	7.2	8.7	6.7	"	0.58
REM	"	16.6	3.5	4.5	17.2	2.5	"	0.15
Stage 2	"	50.4	8.1	6.3	46.8	6.6	"	1.70
SWS	"	20.4	6.7	6.4	22.7	10.1	"	0.50
no. Stage Shifts	136.3	45.2	126.4	29.6	124.7	31.9	"	0.26
Sleep latency (min)	22.8	13.7	22.7	15.4	23.4	12.9	20 ^c	0.01
SWS latency	16.8	9.1	29.5	44.1	28.0	45.1	"	0.39
REM latency	95.9	47.3	88.3	52.8	86.5	38.7	"	0.17
REMP duration	"	24.6	5.9	6.0	29.5	7.6	"	2.66
REMP efficiency (%)	74.2	6.5	71.7	13.0	70.6	8.9	"	0.67
REMP cycle ^d (min)	99.8	15.0	99.4	13.7	96.9	10.7	"	0.21
^a <i>p</i> > .05	^b <i>n</i> = 10	^c <i>n</i> = 11	^d Interval between REM periods.					

2. Reliability

My approach to the assessment of intrasubject and intersubject reliability was somewhat problematic. Traditional reliability studies usually involve many subjects recorded over multiple nights (cf. Wilde-Frenz & Schulz, 1983). Summary measures, such as TST or sleep efficiency are then correlated between nights (intrasubject) and between subjects (intersubject). The limited parameters of the present study (i.e., 11 subjects recorded across three nights) precluded the use of the traditional reliability paradigm and as a result, a more rigorous epoch-by-epoch comparative approach was adopted.

It should be noted that since correlation coefficients were the chief indices of association, significance tests for *goodness-of-fit* were not considered appropriate. It is well known that given a sufficiently large sample, the probability of rejecting the null hypothesis is high and these meaningless significance values could obscure the substantive meaning of the correlation (Pedhazur, 1982). In this particular study emphasis should be placed on the descriptive rather than the inferential interpretation of these measures.

Pearson product-moment correlations between nights were performed on summary sleep parameters and the total accumulated movement count from the right wrist. Coefficients ranged between -0.08 and 0.82 (see Table 3) and simple ordering of the three correlations for each measure revealed a simple trend: (a) highest coefficients were between Night 2 and Night 3; then, (b) Night 1 and Night 3; and finally,

Table 3*Correlation analysis between three consecutive weeknights for traditional sleep parameters.*

Variable	Pearson Product-Moment Correlation (r_{xy})				Cronbach's α
	N1-N2	N1-N3	N2-N3	ECIC ^a	
TST + Stage 1 (min)	.81 ^b	.51	.66	.66	.85
Sleep efficiency (%)	.31	.40	.73	.44	.70
WASO/MT	.34	.41	.73	.44	.71
Stage 1	.46	.70	.41	.42	.68
REM	.35	.45	.76	.46	.72
Stage 2	-.01	.36	.56	.28	.54
SWS	.53	.54	.77	.58	.81
Sleep latency (min)	.30 ^c	.16	-.20	.07	.19
SWS latency	.20	-.07	-.06	-.02	-.05
REM latency	.23	.16	.42	.27	.52
REMP duration	-.08	.52	.59	.37	.64
REMP efficiency (%)	.35	.38	.61	.42	.68
REMP cycle ^d (min)	-.04	.82	.12	.27	.52
Actigraphy (right wrist)	.49	.38	.25	.32	.58
^a Estimated common intravariabile correlation.					
^b $n = 10$					
^c $n = 11$					
^d Interval between REM periods.					

(c) Night 1 and Night 2.

The ECIC, a pseudo average coefficient, was less than 0.30 for percent Stage 2, REMp cycle duration, and latencies to sleep, SWS, and REM onset. Cronbach's α , a robust, liberal measure of association, was noticeably small for latencies to sleep and SWS onset. Taken together with the individual correlations and the ECICs, it is reasonable to conclude that most of the overnight sleep parameters were reliable from one night to the next (cf. Moses et al., 1972).

The alternate approach (i.e., epoch-by-epoch comparison) involved a number of data modifications. As mentioned previously, 32 second epoches were reduced to 4.8 minute epoches. The corresponding stage and movement series were appended, subject by subject, for each night. This resulted in three long columns of sleep stages and movement epoches, respectively. The correlation-based statistics required exact matching across the three nights (i.e., equal numbers of observations), while the percent-concordance index was more flexible (i.e., comparisons between nights could be individually matched).

The results were congruent with and complimentary to those associated with the summary sleep measures reported above. Epoch-by-epoch agreement (% concordance) for sleep staging offered the best indication of reliability between nights. Concordance was approximately 44% between all three nights (see Table 4) and though this value was relatively low, the probability of an individual being in the same sleep stage at the same time, relative to sleep onset, from night to night was better than chance (33%).

Table 4

Reliability measures between three consecutive weeknights for epoch h-by-epoch sleep staging.

Variable	Sleep Stage Epoch Concordance (%)			Kendall's Rank Order Correlation (r_T)			Cronbach's α
	N1-N2	N1-N3	N2-N3	N1-N2 ^a	N1-N3	N2-N3	
Stage Scoring <i>n</i>	41.4 (937)	44.0 (916)	45.9 (929)	.16	.20	.17	.35

Note. Epoch duration is 4.8 min.

Sleep stage score is the bin mode of nine 32 s epochs.

^a *n* = 909 observations.

Kendall's rank order correlations (r_{τ}) were also used to assess the reliability of stages between nights. The three coefficients were each below 0.30, suggesting that the relationship was weak and Cronbach's α was just above the acceptable cut off of 0.30, implicating a marginal association at best. In general, these correlative techniques are very conservative because there is no flexibility (i.e., phase adjustment) built into the algorithms. By design, the sleep stage and BM processes were phase locked to sleep onset and this probably accounts for the weak relationships found between nights.

Intrasubject reliability for the movement index proved to be weaker than the concomitant sleep staging. Pearson product-moment correlations clustered around 0.10 and the ECIC was 0.09 (see Table 5). Cronbach's α was less than 0.30 and taken together, these indices suggest that movement is relatively variable from night to night – more so than for sleep.

A similar battery of measures was used to assess intersubject reliability for both sleep stages and body movement. Data matrices were sorted in a variety of ways to accommodate the statistical routines. For percent epoch concordance, the three nights of sleep stage data for each subject were appended and matched repeatedly at sleep onset for comparison with the other subjects. Basically, this rendered one tenth of the sum redundant on any other subject (i.e., comparisons were repeated).

The values reported in Table 6a are the totals for percent agreement between the designate and the other 10 subjects. The average index was 42.5%, ($SD = 2.5$) and the two subjects with the lowest

Table 5

Reliability measures between three consecutive weeknights of sleep for epoch-by-epoch body movement index.

Variable	Pearson Product-Moment Correlation (r_{xy})				Cronbach's α
	N1-N2 ^a	N1-N3	N2-N3	ECIC ^b	
Actigraphy	.08	.09	.11	.09	.23
<i>Note.</i> Epoch duration is 4.8 min.					
^a $n = 907$ observations.	^b Estimated common intravariabile correlation.				

Table 6a

Reliability measures (% epoch concordance) between subjects for epoch-by-epoch sleep staging.

		Subjects										
		M.W.	K.C.	J.G.	A.W.	W.D.	L.M.	A.P.	J.N.	C.G.	L.S.	J.M.
Sleep Stage												
Concordance	(%)	39.4	44.6	41.6	44.9	42.3	44.4	42.1	41.7	37.3	44.1	44.9
<i>n</i>		(2359)	(1930)	(2423)	(2429)	(2479)	(2529)	(2528)	(2573)	(2465)	(2480)	(2473)
Note. Epoch duration is 4.8 min.												
Sleep stage score is the bin mode of nine 32 s epochs.												

individual values (i.e., Subject 1 [M.W.] and 9 [C.G.]) each complained of difficulty getting to sleep on one of the recording nights. It is also noteworthy that these measures were comparable to those reported between nights, though the sample sizes were dramatically different. Percentage of agreement indices for sleep stages were, again, just better than chance.

Kendall's rank order correlations on sleep stages between subjects were variable (i.e., r_T ranged from - 0.05 to 0.20) and the majority were comparable to the night-by- night coefficients (see **Table 6b**). Again, Subject 1 and 9 as well as Subject 6 had near zero coefficients, suggesting that they were nonrepresentative of the group.

Composite measures of association, such as the corrected subject-total correlation (CSTC), ECIC, and Cronbach's α , are liberal in comparison to individual repeated correlations. The algorithms supporting the CSTC accommodate repeated but separate epoch-by-epoch comparisons between the designate and the other 10 subjects. The advantage in using this procedure is the efficient partitioning of variability across separate correlations which results in a more robust coefficient for describing the relationship between one subject and a group.

A fairly robust corrected subject-total correlation coefficient for sleep stages was present for the subjects who consistently demonstrated strong group concordance, (see **Table 6c**). Again, the 3 subjects who possessed practically no intergroup relationship on the previous measures, showed little improvement. In fact, Subject 9 was negatively

Table 6b

Reliability measures (Kendall's Rank Order Correlation (r_T)) between subjects for epoch-by-epoch sleep staging.

	Subjects										
	M.W.	K.C.	J.G.	A.W.	W.D.	L.M.	A.P.	J.N.	C.G.	L.S.	J.M. ^a
Kendall's (r_T)	.06	.18	.13	.16	.13	.08	.14	.15	-.05	.20	.17

Note. Epoch duration is 4.8 min.
Sleep stage score is the bin mode of nine 32 s epochs.

^a $n = 1930$ observations.

Table 6c

Omnibus reliability measures between subjects for epoch-by-epoch sleep staging .

Corrected Subject-Total Correlation (r_{xy})											ECIC ^a	Cronbach's α
M.W.	K.C.	J.G.	A.W.	W.D.	L.M.	A.P.	J.N.	C.G.	L.S.	J.M.		
.09	.39	.31	.28	.27	.09	.29	.27	-.21	.43	.39	.09	.53

Note. Epoch duration is 4.8 min.

Sleep stage score is the bin mode of nine 32 s epochs.

^a Estimated common intravariabile correlation. ^b $n = 193$ observations.

correlated ($r = -0.21$) with the other subjects.

The estimated common intravariation correlation was low ($r = 0.09$). In contrast, Cronbach's α for sleep staging between subjects was quite large (0.53), attesting to its tendency to inflate as more variables (subjects) are added to the matrix. Comparison with the night by night-based α coefficient (0.35) could be tenuous as a result of this property.

Body movements were grossly unreliable from subject to subject as revealed in Table 7a. Kendall's τ was practically zero in each case (r_τ ranged from -0.03 to 0.03), indicating that trends in movement were extremely variable and that referencing to sleep onset was too strict a criteria for the 4.8 minute epochs. The ECIC was 0.01 and offered a reasonable measure of central tendency for the nonparametric Kendall coefficients (see Table 7b). This value was not dramatically different from the intrasubject coefficient of 0.09. Even Cronbach's α was very low (0.11), attesting to the complete lack of intersubject reliability as measured by the BM index.

3. Movement Cycle

The search for a sleep-based movement cycle was also somewhat problematic. The intention of this exercise was to model the time series of movement and sleep across the night and examine the interrelationships between these phenomena. To accomplish this, a new data reduction scheme was adopted. Raw movement epochs were

Table 7a

Reliability measures (Kendall's Rank Order Correlation (r_T)) between subjects for epoch-by-epoch body movement index.

Subjects												
		M.W. ^a	K.C.	J.G.	A.W.	W.D.	L.M.	A.P.	J.N.	C.G.	L.S.	J.M.
Kendall's	(r_T)	-.01	.02	.03	-.03	.02	-.01	.03	.03	-.02	.02	-.01
<i>Note.</i> Epoch duration is 4.8 min.												
^a n = 1930 observations.												

Table 7b

Omnibus reliability measures between subjects for epoch-by-epoch body movement index.

Corrected Subject-Total Correlation (r_{xy})												
										ECIC ^a	Cronbach's α	
M.W.	K.C.	J.G.	A.W.	W.D.	L.M.	A.P.	J.N.	C.G.	L.S.	J.M.	^b	
-.02	.09	.13	-.11	.10	-.03	.11	.09	-.06	.14	-.01	.01	.11

Note. Epoch duration is 4.8 min.

^a Estimated common intravariabile correlation. ^b $n = 193$ observations.

reduced to 3.2 minutes, beginning at sleep onset, and time series analyses were performed on each of the 33 actigrams as well as the averaged facsimile.

Simulating a set of sleep stage time series was more challenging. Thirty-three PSGs were aligned with sleep onset and parceled into six epoch-long blocks. These bins held a maximum of 198 individual stage epoches (i.e., six epoches by 33 records) and a frequency distribution was determined for each bin. The result was a percent-stage content index for each 3.2 minute bin. These percentage epoch values were the continuous dependent measures for the individual sleep stages.

Two techniques were used to model the data; Box-Jenkins time series analysis (Norusis & SPSS Inc., 1988) and orthogonal polynomial regression (Dixon et al., 1990). Both methods compliment one another (i.e., Box-Jenkins time series is particularly suited for detecting periodicities or cycles while polynomial regression is useful for smoothing data and indicating trends).

Individual actigrams were fitted with curves modeled by Box-Jenkins autoregressive integrated moving-average algorithms (ARIMA). The specific parameters are voluminous in text and will not be reported in this document. The data are summarized below as well as in **appendix E**. The individual models were diverse, incorporating different combinations of ARIMA components. Five records failed to have a movement cycle while the other 28 generally clustered into a trimodal distribution with respect to periodicity. Specifically, the first group (19 records) ranged between 60.8 and 73.6 minutes with a mode at

73.6 minutes (six records). A second peak was also evident at 67.2 minutes (five records), and together, the first group accounted for 58% of all the recordings. The second group was characterized by a single peak at 89.6 minutes (four records) which corresponded to the REM-nonREM cycle. The average periodicity for all the movement series with cycles was 73.8 minutes ($SD = 11.6$ min).

The 33 actigrams were aligned at sleep onset and averaged to produce a single series. Orthogonal polynomial regression and Box-Jenkins time series analysis were performed, separately (see **Figure 2**). The regression resulted in a 5th degree polynomial curve approximating the process. Pictorially, the curve rises dramatically to peak after 1 hour of sleep. It descends to a mid-series nadir at roughly 3 hours and then ascends gradually across the remaining duration until it rises sharply at the end. This latter aspect probably corresponds to the *crescendo effect* reported by Laird (1935). The sharp rise at the end is concomitant with the increased probability of morning awakening.

The Box-Jenkins model incorporated autoregression and cyclical moving-average components at the first degree, respectively. A significant period of 67.2 minutes emerged as well. This corresponded to one of the principal peaks present in the first group of individual actigrams. The ARIMA model tracked the progression of the raw data well, but failed to mirror the amplitude displacements of the largest fluctuations.

Table 8 shows relevant parameters associated with both the ARIMA and polynomial regression models. All of the components for each *fit*

Figure 2. ACTIGRAPHY. Polynomial regression and Box-Jenkins time series fitted curves for movement data. Epochs are 3.2 min and begin at sleep onset. Raw counts are transformed $[\ln(x+1)]$ and averaged.

Table 8

Box-Jenkins time series and polynomial regression analyses of body movement index and % sleep stages.

Variable	M ^a (SD)	Model	Period (min)	SS(fit) (df)	SS(res) (df)	Mean Square error	Durbin Watson statistic	R ²
Actigraphy	3.45 (0.37)	ARIMA (1,0,0)(0,0,1)	67.2	2.6 (2)	14.6 (124)	0.34	2.07	.15
		5 th order polynomial		3.8 (5)	13.3 (121)	0.33		.22
% Wake	8.51 (7.53)	ARIMA (0,1,1)		5182.4 (1)	897.2 (125)	2.68	1.92	.85
		7 th order polynomial		6594.7 (7)	551.7 (119)	2.15		.92
% Stage 1	3.99 (3.89)	ARIMA (1,0,0)(1,0,0)	70.4	601.6 (2)	1303.0 (124)	3.24	2.03	.32
		4 th order polynomial		517.2 (4)	1388.4 (122)	3.37		.27

Note. Epoch duration is 3.2 min.

^a *n* = 127 observations.

Table 8 (continued)

<i>Box-Jenkins time series and polynomial regression analyses of body movement index and % sleep stages.</i>									
Variable	<i>M</i> ^a (<i>SD</i>)	Model	Period (min)	<i>SS</i> (fit) (<i>df</i>)	<i>SS</i> (res) (<i>df</i>)	Mean Square error	Durbin Watson statistic	<i>R</i> ²	
% REM	15.89 (8.75)	ARIMA (1,0,0)(0,1,1)	86.4	5494.9 (2)	1998.6 (97)	4.54	1.95	.73	
		2 nd order polynomial		6312.4 (2)	3337.0 (124)	5.19		.65	
% Stage 2	46.04 (12.91)	ARIMA (1,1,0)(0,0,1)	83.2	21628.6 (2)	3777.3 (124)	5.52	2.0	.85	
		11 th order polynomial		17556.4 (11)	3433.5 (115)	5.46		.84	
% SWS	20.57 (19.61)	ARIMA (1,1,1)(0,0,1)	83.2	5077.7 (3)	2544.1 (123)	4.55	1.96	.95	
		12 th order polynomial		46897.2 (12)	1578.6 (114)	3.72		.97	

Note. Epoch duration is 3.2 min.

^a *n* = 127 observations.

were significant at $p < .05$. Sums of squares and mean squares were roughly equal for the two procedures, as well. The Durbin-Watson statistic represents the degree of unwanted autoregression present in the residual time series which remains after modeling. This value can range from 0 to 4 and a value of 2 indicates that all of the confounding autoregression has been accounted for by the curve approximation. Clearly, the Durbin-Watson statistic shows that the fit removed practically all of the autoregression and that the residuals are relatively independent of one another. Another indicator of goodness-of-fit is the squared multiple correlation coefficient (R^2) which accounts for the proportion of variance in the dependent variable (raw data), explained by the independent variables (model components). The squared multiple correlation coefficients for this ARIMA model ($R^2 = 0.15$) and the polynomial regression model ($R^2 = 0.22$) were relatively small, indicating that other predictors or leading factors such as the corresponding sleep stage series could account for much of the unexplained variability.

Each of the principal stage classifications (i.e., %Wake, %Stage 1, %REM, %Stage 2, and %SWS) was submitted to the same regimen of statistical routines as the averaged actigram (again, see **Table 8**). The %Wake time series was best characterized by a relatively flat progression of near zero percent content for the first 4 hours after sleep onset. The next 2 hours revealed a smooth linear increase until the final hour, when a dramatic exponential increase terminated the process (see **Figure 3**). A 7th degree polynomial was used to fit the data ($R^2 = 0.92$) and Box-Jenkins time series analysis revealed no significant periodic oscillations.

Figure 3. WAKE. Polynomial regression and Box-Jenkins time series fitted curves for % WASO/MT data. Epochs are 3.2 min and represent a frequency percentage of six 32 s epochs by 33 records.

The Box-Jenkins model was comparable to the regression model (i.e., $R^2 = 0.85$) and the level of autoregression present in the residual time series was minimal (i.e., Durbin-Watson statistic = 1.92), suggesting that the fit was acceptable.

Percent Stage 1 was similar to %Wake during the first 5 hours. The process was low and constant in percent epoch content until the final 2 hours when a noticeable increase, commensurate with %Wake, was evident (see Figure 4). Polynomial regression resulted in a 4th order model being fitted to the data ($R^2 = 0.27$) and this was similar to the multiple squared correlation coefficient (0.32) produced by the ARIMA model. A significant rhythm of 70.4 minutes was found and the model was deemed suitable (i.e., Durbin-Watson statistic = 2.03).

It is worth noting that %Stage 1 and the averaged actigram were alike in many respects. For example, both processes were difficult to fit and based on polynomially-derived R^2 values for each (i.e., 0.27 and 0.22, respectively), it is reasonable to suggest that the same predictors could account for a large portion of the unexplained variability common to both. Similar rhythmic cycles (i.e., 70.4 min and 67.2 min, respectively) were evident in both processes. The polynomial order for goodness-of-fit was practically the same (i.e., 4th and 5th degrees, respectively) and the ARIMA models were similar (i.e., (1,0,0)(1,0,0) and (1,0,0)(0,0,1), respectively).

The %REM time series was characterized by no activity during the first 45 minutes and then a gradual increase over the remainder of the night. Superimposed on this trend was a faster wave of oscillations with

Figure 4. STAGE 1. Polynomial regression and Box-Jenkins time series fitted curves for % Stage 1 data. Epochs are 3.2 min and represent a frequency percentage of six 3.2 s epochs by 33 records.

peaks spaced approximately 90 minutes apart (see **Figure 5**). A quadratic polynomial was used to fit the data ($R^2 = 0.65$) and Box-Jenkins time series analysis revealed a significant rhythm of 86.4 minutes. This was very close to the REM-nonREM cycle (approximately 90 min) commonly reported (e.g., Dement et al., 1957) and was not too disparate from the average REM period cycles for individual nights reported in **Table 2** (i.e., 99.8, 99.4, and 96.2 min).

Percent Stage 2 followed an interesting pattern with the first 10 minutes showing very high epoch content followed by a sharp exponential drop to very low values (see **Figure 6**). This nadir was rapidly replaced by a dramatic rise in Stage 2 and a leveling off at about the 50% mark around 1 hour into the process. The remaining 6 hours showed a rhythmical fluctuation of roughly 90 minutes marked by an ebb and flow between 40 and 60% content, probably due to a corresponding increase in %Wake and %Stage 1. The best orthogonal polynomial fit ($R^2 = 0.84$) was obtained with an 11th order equation and the comparable Box-Jenkins time series model ($R^2 = 0.85$) revealed a significant 83.2 minute rhythm.

The final stage process was %SWS which was described by an exponential rise from 0 to 85% within the first 40 minutes. Then an equally precipitous drop to 20% occurred within the next 40 minutes. Interestingly, this portion of the curve is the inverted image of the same portion of the %Stage 2 curve. This rise and fall occurred several more times, only with steadily decreasing amplitudes, approximately every 80 minutes (see **Figure 7**). Polynomial regression resulted in a 12th order

Figure 5. REM. Polynomial regression and Box-Jenkins time series fitted curves for % REM data. Epochs are 3.2 min and represent a frequency percentage of six 32 s epochs by 33 records.

Figure 6. STAGE 2. Polynomial regression and Box-Jenkins time series fitted curves for % Stage 2 data. Epochs are 3.2 min and represent a frequency percentage of six 32 s epochs by 33 records.

Figure 7. SWS. Polynomial regression and Box-Jenkins time series fitted curves for % SWS data. Epochs are 3.2 min and represent a frequency percentage of six 32 s epochs by 33 records.

equation explaining the data ($R^2 = 0.97$) and the ARIMA model ($R^2 = 0.95$) pulled out an 83.2 minute rhythm.

It is noteworthy that, like the actigram and %Stage 1 – %SWS and %Stage 2 were very similar in many respects. For example, both raw data curves were fitted with similar models (i.e., 12th and 11th order polynomials; *ARIMA* (1,1,1)(0,0,1) and (1,1,0)(0,0,1) with the same 83.2 minute rhythm, respectively). This evidence supports the contention that Stage 2 and SWS are merely components of the same nonREM sleep continuum.

Pursuant to the modeling exercise, relationships between BM and individual sleep stages were examined. To accomplish this, a modified *transfer-function* procedure, as described in Dixon et al. (1990), was used. Basically, this involves fitting Box-Jenkins curves to the raw time series of the variables of interest and then cross-correlating the residual processes while allowing for phase alignment. Once the best possible correlations have been determined, the residual series are realigned with respect to the degree of phase shift and multiple regression is performed.

The cross-correlations between the actigram's residual time series and the individual percentage stages' residual time series are presented in **Table 9a**. Essentially, the greater the phase drift (i.e., the larger the absolute value of the lag or lead) the weaker the relationship between the dependent variable (actigram) and the predictor variables (% sleep stages). Percent REM and %Stage 2 seemed to have the weakest relationship with BM, while %Wake had the strongest ($r = 0.66$). Percent Wake and %SWS were in phase with the actigram, while the

Table 9a*Cross correlations between body movement index and % sleep stages*

Stage	Shift (Lag/Lead)	Pearson Product-Moment Correlation (r_{xy})	<i>df</i>
% Wake	0	.66**	126
% Stage 1	-1	.26**	126
% REM	+8	- .26*	92
% Stage 2	+5	.19*	121
% SWS	0	- .28**	126

Note. All variables are comprised of the residual error remaining after their respective time series profiles.

Epoch duration is 3.2 min.

* $p < .05$

** $p < .01$

correlation with %Stage 1 was lagged by one epoch, only.

In general terms, BM and the appearance of wakefulness were concomitant and directly related. The appearance of SWS was also concomitant with BM but was related inversely. Stage 1 led the actigram by one epoch and the direct relationship implied that an increase in BM was followed by an increase in Stage 1, 3.2 minutes later.

Once the sleep stage residual series were adjusted for phase displacement with the residual actigram series, stepwise multiple regression (Norusis & SPSS Inc., 1988) was used to examine relationships between the stages and the BM index. Percent Wake was the only contributing variable and it accounted for 55% of the variability present in the movement series (see **Table 9b**). The influence of the other four %Stage processes was assessed by excluding %Wake from a second regression analysis. All of these stages entered the regression ($R^2 = 0.19$). Notwithstanding, together they could not begin to account for the variance attributed to %Wake. These results are not surprising in light of the magnitude and phase relationship of the cross-correlation between BM and %Wake and the obvious movement-filled nature of wakefulness.

Sleep Parameters

The second major part of this study was undertaken to expand upon the time series work introduced earlier. The raw 32 second epoches of

Table 9b

Stepwise multiple regression analysis of % sleep stages on body movement index.

Stepwise Variable	Multiple R	Adjusted R ²	SS (fit) (df)	SS (res) (df)	Mean Square error	F Ratio	Durbin Watson statistic
Loading							
% Wake	.74	.55	5.02 (1)	4.07 (89)	0.05	109.9*	1.86
% Stage 1	-						
% REM	-						
% Stage 2	-						
% SWS	-						
<hr/>							
% SWS	.28	-					
% REM	.36	-					
% Stage 2	.42	-					
% Stage 1	.47	.19	2.03 (4)	7.07 (86)	0.08	6.17*	2.14

Note. Regression performed on time series residual error. Epoch duration is 3.2 min.

* $p < .001$

the BM index were sorted with respect to sleep stage shifts and sleep stages. Basically, each of the 33 sleep records were scrutinized and broken down, in a stepwise manner, into major stage shifts and sleep stages. First, the stage shifts were extracted from the records. A stage shift was classified if it met several criteria: (a) It had to have at least six epoches of the new stage (i.e., the stage being entered) embedded in the eight epoches sampled; and (b) the two odd epoches had to be preceded by valid stage epoches (i.e., they could not begin the stage). The four epoches prior to the new stage onset were considered the previous stage (i.e., the stage being exited). Only five stage transitions: (a) Stage2 - SWS ; (b) Stage 2 - REM ; (c) REM - Stage 2 ; (d) Stage 1 - Stage 2 ; and (e) SWS - Stage 2) were selected for comparison because they occurred universally. Others, such as SWS - REM and Stage 2 - Wake, were not commonplace and were ignored. Each category of stage shift was averaged by subject for statistical comparison and then the time series were averaged across all subjects for modeling.

All of the remaining epoches per subject were sorted by stage and averaged. In addition, actual stage time series were identified (minus the epoches devoted to the shifts) and grouped in a similar fashion to that of the stage shifts. A single stage series had to be at least 10 epoches in length to be considered. Again, averaging across subjects produced separate stage processes that could be plotted and modeled.

It is important to note that the following analyses are based on average BM counts per subject and that their values may be weighted unequally as a result of varying sample sizes. For example, the average

BM count for Stage 2 sleep is based on approximately two to three times as many observations as for SWS or REM. The procedure adopted for reducing these data resulted in the stage shifts and the stages being mutually exclusive events. No overlap was tolerated in an effort to dissociate both phenomena.

1. *Sleep Stages*

Within-subjects one-way ANOVA was conducted on the average BM index for five sleep stages (see **Table 10a**). The Geisser-Greenhouse adjusted F test was highly significant, $F(2, 21) = 916.5$, $p < .001$ and Newman-Keuls post hoc pairwise comparisons were used to isolate the differences (Kirk, 1982). **Table 10b** reveals a marked trend for declining rate of movement as a function of sleep stage (i.e., WASO > Stage 1 > REM > Stage 2 > SWS). The only comparison that did not reach statistical significance was between Stage 2 ($M = 0.25$) and SWS ($M = 0.15$). Although a trend was present, a number of factors may have biased against finding a significant difference in the omnibus test as a result of including Stage 1 and Wake in the analysis: (a) the variability ($SD = 0.13$ in both cases); (b) the raw data sampling differential; and (c) the loss of power (Geisser-Greenhouse $\epsilon = 0.53$).

Individual stage series were plotted and each was submitted to a set of 12 standard curve-fitting algorithms (Norusis & SPSS Inc., 1988). Given the abbreviated length of these processes (e.g., 24 epoches of Stage 2), any significance attached to the fitted curves beyond descriptive

Table 10a*Analysis of variance of body movement index for sleep stages*

<i>Source of Variance</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>
A (Stage)	110.40	4 ^a	27.60	916.5* @
A(error)	1.20	40	0.03	

Note. Post-hoc analysis is presented in Table 9b.^a $n = 11$ * F test [conventional]; $df(4,40)$; $p < .001$ @ F test [Geisser-Greenhouse adjusted]; $df(2,21)$; $p < .001$

Table 10b

Newman-Keuls pairwise comparisons of body movement index for sleep stage stages

Sleep Stage <i>M</i> (<i>SD</i>)	Stage 2	REM	Stage 1	Wake
SWS 0.15 (0.13)	0.10	0.30**	1.06**	3.78**
Stage 2 0.25 (0.13)	-	0.20*	0.96**	3.69**
REM 0.45 (0.21)		-	0.76**	3.48**
Stage 1 1.21 (0.39)			-	2.72**
Wake 3.93 (0.26)				-
* $p < .05$		** $p < .01$		

bounds, would be suspect. All of the curves were polynomial in nature (see **Figure 8**) and only REM and Stage 2 incorporated constants in their equations.

Not surprisingly, WASO showed very high BM counts and the cubic curve was best characterized as a burst of activity lasting only four or five epoches, with lower counts at either end signaling the onset and termination of this burst. Stage 1 was equally short in duration and was fitted as a cubic curve as well. The process was variable; however, it seemed to increase in magnitude with time.

REM, Stage 2, and SWS were flatter and less variable. REM sleep was cubic in nature with the first three or four epoches showing an increase in BM count followed by an equally gentle drop. This nadir was framed on the right side by another rise which may have been the beginning of a repeat of the first 10 epoches (i.e., the onset of a within-stage cycle). Stage 2 was quadratic in nature and was characterized by a flat process with a small rise at the end which may have been coincidental with the expected stage shift. Slow Wave sleep was also quadratic but it followed a constant, gentle increase, reaching its zenith by the 11th epoch.

2. Sleep Stage Shifts

One-way, within-subjects ANOVA was also used to analyze the average BM index for the five sleep stage shift classifications (see **Table 11a**). The Geisser-Greenhouse adjusted *F* test was highly significant,

Figure 8. SLEEP STAGES. Average body movement index for sleep stages as a function of time. Epochs are 32 s means of transformed $[\ln(x+1)]$ raw counts.

Table 11a*Analysis of variance of body movement index for sleep stage shifts*

<i>Source of Variance</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>
A (Stage Shift)	4.69	4 ^a	1.17	19.3* @
A(error)	2.43	40	0.06	

Note. Post-hoc analysis is presented in Table 10b.^a $n = 11$ * F test [conventional]; $df(4,40)$; $p < .001$ @ F test [Geisser-Greenhouse adjusted]; $df(2,23)$; $p < .001$

$F(2, 23) = 19.3$, $p < .001$ and Newman-Keuls post hoc pairwise comparisons revealed a number of significant differences between stage transitions (see **Table 11b**). Basically, there was very little movement associated with the shift from Stage 2 to SWS and the average count was significantly different from all the other categories.

The Stage 2 to REM shift ($M = 0.49$) was not significantly different from the reverse transition (i.e., REM to Stage 2; $M = 0.63$), suggesting that movement between these stages may be facilitated by a common mechanism. The transition between SWS and Stage 2 involved the greatest average BM index but it was not different from the Stage 1 to Stage 2 (the sleep onset process) shift. This result may have been coincidental since no apparent relationship between these two transition states is obvious.

Individual stage shift series were plotted and treated similarly to the stage series with respect to curve-fitting procedures (see **Figure 9**). Again, I must emphasize that these processes are only 12 epoches long and thus, the utility of such an exercise is suspect beyond the ability to describe the series. All of the curves were polynomial in nature and only the Stage 1 to Stage 2 shift involved a constant in the equation. This particular shift was linear, showing a moderate decline in movement from Stage 1 into the deeper sleep of Stage 2.

The drop from Stage 2 into SWS was characterized by a relatively flat, cubic series with very low levels of movement. The inverse transition from SWS to Stage 2 was dramatically different in comparison. This quadratic curve was best described by a sharp exponential rise in BM

Table 11b

Newman-Keuls pairwise comparisons of body movement index for sleep stage shifts.

Stage Shift <i>M</i> (<i>SD</i>)	St 2-REM	REM-St 2	St 1-St 2	SWS-St 2
St 2-SWS 0.17 (0.17)	0.32**	0.46**	0.77**	0.78**
St 2-REM 0.49 (0.23)	-	0.14	0.45**	0.46**
REM-St 2 0.63 (0.28)		-	0.31*	0.32*
St 1-St 2 0.94 (0.57)			-	0.01
SWS-St 2 0.95 (0.42)				-
* $p < .05$ ** $p < .01$

Figure 9. STAGE SHIFTS. Average body movement index for stage shifts as a function of time. Epochs are 32 s means of transformed $[\ln(x+1)]$ raw counts.

across the SWS epoches and on into Stage 2, eventually peaking by the fourth epoch. This was followed by an equally striking decline over the remaining series as Stage 2 stabilized after the abrupt arousal.

The shift from Stage 2 to REM was cubic in nature, showing a gradual rise in movement counts which peaked at the actual transition point and then gently declined over most of the remaining process. A short upturn at the end may have been signaling the onset of the oscillatory phenomenon seen in the REM stage process. The inverse transition, REM to Stage 2, was clearly more robust and the quadratic curve depicted a rapid increase in BM over half the entire process. This was followed by a mirror-like decline as body movements stabilized with the establishment of Stage 2.

3. *Sleep/Wake Scoring*

The ultimate aim in performing the time series analyses and the stage - stage shift analyses was, aside from any intrinsic interest, to lay the groundwork for development of a mechanism by which Sleep/Wake states could be predicted from BM indices. To effect this task, BM was regressed upon a binary (Sleep/Wake) variable using stepwise logistic regression (Dixon et al., 1990). All 33 polysomnographic listings were restaged as Sleep (Stage 1, REM, Stage 2, or SWS) and Wake (WASO or MT) on an epoch-by-epoch basis. Seventeen of the 33 records were chosen randomly and appended into one long series. The corresponding actigram was phase-lagged from 1 to 10 epoches and phase-led from one

to five epoches, resulting in 16 predictor variables. For example, a single sleep stage epoch was matched with its concomitant movement count as well as the previous count; and the count before that; and so on for eight more epoches before the actual event. Likewise, this sleep epoch was also matched with the next movement count following its concomitant BM epoch; and the next one and so on for three more epoches after the actual event. This arrangement accounted for any context-based information inherent to the BM series that might improve or enhance the prediction of the Sleep/Wake states (i.e., a moving window device).

The model parameters are presented in Table 12a. Only 2 of the 16 variables entered the equation; the actual concomitant BM epoch (i) and the epoch immediately proceeding it ($i + 1$). The nonsignificant goodness-of-fit chi square ($\chi^2 [1301, N = 14,708] = 1148.7, p = 1.0$) suggested that the logistic model provided a reasonable approximation to the data. The equation was expressed in terms of the probability of detecting an epoch of Wake (i.e., if $\rho(\text{Wake}) \geq 0.5$, the epoch was scored Wake; if $\rho(\text{Wake}) < 0.5$, the epoch was scored Sleep).

Each of the 17 overnight records were then trimmed to just the two key actigraph variables matched with the binary Sleep/Wake variable. The algorithm was introduced and the BM counts were transposed into Sleep and Wake epoches. This resulted in two parallel series of binary codes (Sleep/Wake), one originating with the polysomnogram and the other derived from the actigraph. The 17 records were appended and an epoch-by-epoch comparison for concordance was performed. ~~The results~~ are presented in Table 12b.

Table 12a

Model parameters for the Sleep/Wake recognition algorithm derived by stepwise logistic regression.

MODEL PARAMETERS

Number of distinct covariate patterns = 1304

Log-likelihood estimation = - 1263.9

Goodness of fit (χ^2) = 1148.7 ; $df(1301)$; $p = 1.0$

Term	Coefficient	Standard Error(coeff.)
Constant	-6.518	0.162
(i)	1.760	0.049
(i+1)	0.146	0.030

$$\text{EQUATION: } \rho(\text{Wake}) = \frac{e^{-6.518 + 1.76(i) + 0.146(i+1)}}{1 + e^{-6.518 + 1.76(i) + 0.146(i+1)}}$$

Table 12b

Comparison of actigraph-based Sleep/Wake staging with PSG-based staging for retrospective data.

		Actigraph					
Somnograph	epochs	Wake		Sleep		Total	
		(min)	(%)	(min)	(%)	(min)	(%)
Wake	967	366.9	71.2	148.8	28.9	515.7	{6.6}
Sleep	13,741	93.9	1.3	7234.1	98.7	7328.0	{93.4}
Total	14,708	460.8	{5.9}	7382.9	{94.1}	7843.7	{100.0}

Classification	PSG - Wake		PSG - Sleep		Total	
	(min)	(%)	(min)	(%)	(min)	(%)
Concordant (hits)	366.9	4.8	7234.1	95.2	7601.0	{96.9}
Discordant (misses)	148.8	61.3	93.9	38.7	242.7	{3.1}
Total					7843.7	{100.0}

Of the 967 epoches of Wake actually sampled, 71% were correctly identified by actigraphy. Clearly, the algorithm did a much better job of predicting Sleep (i.e., 98.7% of the 13,741 epoches sampled were matched with the PSG) than Wake. Taken together, the actigraph was scoring Wake and Sleep accurately 96.9% of the time. Of the discordant epoches or misses (3.1%), the actigraph was misscoring Wake twice as often as Sleep. It is obvious that the algorithm becomes less efficient when subjects lie awake, motionless.

These results are statistically biased for the best possible prediction because of the common source of data used to develop and test the algorithm. A prospective test was undertaken with the remaining 16 overnight records in order to cross-validate the findings. The data were set up identically to those in the retrospective sample. The retrospective-based algorithm was implemented under exactly the same parameters and, though there were fewer epoches, results were remarkably similar to their retrospective counterparts (see **Table 13a**).

Of the 816 epoches of Wake sampled, 68% were correctly identified by actigraphy. Again, the actigraph did a much better job with identifying Sleep (i.e., 98.9% of the 12,698 epoches sampled were matched with the PSG). Taken together, the actigraph was scoring Wake and Sleep accurately 96.9% of the time, as well. Of the discordant epoches or misses (3.1%), the actigraph was, again, misscoring Wake twice as often as Sleep.

Although the epoch-by-epoch reliability index showed that the PSG- and actigraph-based staging schemes were very close, other indices

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

Table 13a

Comparison of actigraph-based Sleep/Wake staging with PSG-based staging for retrospective data.

Somnograph	epochs	Actigraph					
		Wake		Sleep		Total	
		(min)	(%)	(min)	(%)	(min)	(%)
Wake	816	296.0	68.0	139.2	32.0	435.2	{6.4}
Sleep	11,882	69.9	1.1	6252.3	98.9	6322.1	{93.6}
Total	12,698	365.9	{5.4}	6391.5	{94.6}	6757.3	{100.0}
Classification	PSG - Wake		PSG - Sleep		Total		
	(min)	(%)	(min)	(%)	(min)	(min)	(%)
	(min)	(%)	(min)	(%)	(min)	(min)	(%)
Concordant (hits)	296.0	4.5	6252.3	95.5	6548.3		{96.9}
Discordant (misses)	139.2	66.6	69.9	33.4	209.1		{3.1}
Total					6757.3		{100.0}

of reliability such as Pearson product-moment correlations and dependent t tests based on individual subject data, were also used to substantiate this powerful relationship. This alternate approach allowed for the sectioning of the overnight recording into the period of time involved with falling asleep and the actual sleep period itself. A subsequent assessment of whether the actigraph was particularly weak in predicting wakefulness when the subject was trying to fall asleep, (i.e., presumably remaining motionless while awake) was performed. Each of the 16 prospective sleep recordings was partitioned into the sleep onset period, defined as the interval between lights out and sleep onset, and the sleep period, defined as the interval between sleep onset and morning awakening. Total minutes of Sleep and Wake for each time period were obtained from the PSG and the transposed actigram of each recording (see Table 13b). Dependent t tests were used to detect differences between the two methods of scoring Sleep and Wake. All six comparisons were nonsignificant, attesting to the fact that the two methods were remarkably similar.

Pearson product-moment correlations for TST were very high (e.g., $r_{(TIB)} = 0.97$) and all the correlations were significant at $p < .001$. The correlations for total Wake time were not as great (e.g., $r_{(TIB)} = 0.76$) but this was probably due to the larger relative difference between the PSG and actigraph means as compared to the corresponding Sleep values. Examination of the mean differences for Wake time revealed a tendency for the actigraph to overscore Sleep (i.e., the mean duration of Wake scored by the actigraph was universally less than the mean for the

Table 13b

Correlation and dependent t test analyses between PSG-based and actigraph-based Sleep/Wake staging.

Sleep/Wake Score	Polysomnograph		Actigraph		Pearson Product a Moment Correlation (r_{xy})	Paired b t test
	M	SD	M	SD		
<u>Sleep Onset Period</u>						
Sleep (min)	19.7	13.8	20.4	13.9	.99	- 1.14
Wake "	6.7	4.2	6.0	4.4	.86	1.15
<u>Sleep Period</u>						
Sleep (min)	376.3	45.1	380.0	44.3	.98	- 1.70
Wake "	20.5	14.5	16.9	12.7	.81	1.70
<u>Time In Bed</u>						
Sleep (min)	396.3	40.5	400.4	40.2	.97	- 1.70
Wake "	27.2	15.1	22.9	13.5	.76	1.72

Note. Sleep onset period is the interval between "lights-out" and sleep onset (start of 3 min of continuous Stage 2). Sleep period is the interval between sleep onset and morning awakening.

a *df* (14); *p* < .001

b *p* > .05

polysomnogram).

To obtain comparative measures of the efficacy of the actigraph during the sleep onset period versus the sleep period, percent differences (M_{diff} / M_{PSG}) for Sleep time were derived for each. Based on the results (i.e., sleep onset [3.6%] and sleep period [1.0%]), one can conclude that the actigraph was more accurate in detecting wakefulness during the sleep period than during the shorter sleep onset period. This finding confirms earlier observations by Webster et al. (1982) that in order to bring on sleep we try to restrain our movements. This conscious action of lying still in bed during the sleep onset process is primarily responsible for the staging errors committed by the algorithm and its performance may be improved with a better understanding of the nature of Stage 1 sleep (i.e., differentiating Stage 1 into sub-classes such as Stage 1a and 1b), which was the principal sleep stage evident in the sleep onset period.

DISCUSSION

Movement Parameters

An overriding concern with this study was that the subject's sleep be as natural as possible. The use of ambulant monitoring and the placement of very few restrictions on personal sleeping habits were some of the steps taken to ensure that this condition was preserved. Control over potentially confounding sources of error such as a bed partner, ambient noise and temperature, and individual bedtime routine was relaxed in order that the "real" BM and PSG profiles would not be compromised. In my opinion, this unique opportunity to record sleep and BM in the subject's normal sleep surroundings was worth this margin of uncertainty.

1. First Night Effect, Laterality, Limb Differentiation

The data concerning the first night effect were not congruent with traditional sources (Agnew et al., 1966; Mendels & Hawkins, 1967; Schmidt & Kaelbling, 1971) which argue that the first night spent sleeping in the laboratory is adversely affected by an increased state of vigilance or arousal in the subject. The fact that no *first night effect* was found on any single measure derived from either the sleep architecture or the BM index supports the hypothesis that the lack of familiarity with the sleeping

environment is the principal factor behind the appearance of this phenomenon.

The recordings, collected under at-home sleeping arrangements were, indeed, first night effect-free (Dunham, Broughton, & Hoffmann, in press) and were well within normative ranges (Williams, Karacan, & Hirsch, 1974). Others have reported a significant reduction or complete elimination of the first night effect as a result of making the laboratory sleep chamber homely or actually recording in the subject's home (Coble, McPartland, Silva, & Kupfer, 1974; Coates, George, Killen, Marchini, Hamilton, & Thorensen, 1981; Sharpley, Solomon, & Cowan, 1988). Mean values for the parameters derived from the polysomnogram (Table 2) were astonishingly similar to those reported by Sharpley et al. (1988), who, incidentally, employed the Medilog recorder and the same ambulant, triple night paradigm. Coble et al. (1974) included wrist movement in their assessment of the first night effect and found no differences which they attributed to their comfortable sleep chamber.

A very recent study by Kaartinen and Lyytinen (1990) using the *static-charge sensitive bed*, showed a paradoxical decrease in movement from the first night to the second when subjects were recorded at home. A movement rebound was evident on the third night and they concluded that subjects can be psychologically stressed even in a familiar environment with minimal physical discomfort.

Other than this single report, a consensus is emerging amongst those who show concern for the sleeper's external surroundings (i.e., the first night effect can be minimized by altering the laboratory setting).

Special attention to the design – decor and the presleep protocol for hookups could reduce or negate the degree of nervous involvement experienced by the sleeper which presents itself as the first night effect. With the growth of ambulant monitoring technology and the ever rising costs associated with discarding the first night's in-lab sleep recording, in-home polysomnography may be an inexpensive and viable alternative to more traditional methods.

One of the most intriguing and certainly, thought provoking discoveries from this study concerned the interaction between body laterality and limb differentiation (Dunham, Hoffmann, & Broughton, 1990). The left wrist moved more during sleep than any of the other three corresponding sites. In fact, the right wrist, right ankle and left ankle registered roughly equal magnitudes. This finding is in agreement with and lends credibility to the claims of others (Muller-Limroth, 1965; Jovanovic, 1971; Gardner & Grossman, 1975). From a practical point of view, knowing that the left wrist of right-handers is the most sensitive site for recording movement during sleep, we can establish sound criteria for protocols and procedures involving overnight motility monitoring.

Lauerma, Lehtinen, and Holmstrom (1990) have just recently presented confirmatory evidence using bilateral wrist actigraphs in left- and right-handers. They report a substantial dominance reversal for movement in both groups (i.e., the right arm of left-handers moved more while the left arm of right-handers moved more; during sleep).

The implications of this research are far reaching with respect to brain function and sleep. Muller-Limmroth (1965) proposed a

fatigue-rest hypothesis to explain the phenomenon. Briefly, the idea holds that the structures mediating the function of the dominant side are more frequently active during waking and thus require more rest during sleep. For this reason, the dominant hand would be less active at this time. The data support the notion of just such an oscillatory mechanism mediating limb movements. A comprehensive study, incorporating actigraphy and videography in matched left- and right-handers, could begin to unravel the significance of these movements. Special attention, paid to the differences between organized and unorganized movements as a function of laterality and temporal distribution, could influence our current understanding of dreaming, verbal/visual-spatial modes of information processing, or even the *unconscious*.

2. Reliability

My attempt to assess the reliability of movements and sleep over consecutive nights and between individual subjects was an interesting mix of improvisation, compromise and perseverance. The difficulties encountered in working with epoch-by-epoch comparisons easily justifies why this type of analytic approach has no precedent in the literature. Of course, I was able to study intrasubject reliability in the traditional fashion (Table 3) and the results were comparable to those of Moses et al. (1972) for sleep parameters and Wilde-Frenz and Schultz (1983) for body movement. The only two measures that showed practically no visible relationship between nights were the latency to sleep, and SWS onset.

These measures would be particularly sensitive to a subject's personal idiosyncrasies (i.e., willful changes to the bedtime routine or experiencing difficulty falling asleep).

Most of the sleep parameters showed similar or stronger correlations between nights as compared to previous reliability studies. The strength of this generalization is diminished by the fact that Moses and associates tested 20 subjects instead of eleven. In terms of magnitude, most of the correlations were above 0.30, suggesting that gross parameters of sleep and BM are reliable from night to night.

The alternative epoch-by-epoch comparative approach was more difficult to interpret than the analysis mentioned above. The same issues were addressed (i.e., intrasubject and intersubject reliability) but the method was more restrictive. Two principal factors responsible for this drawback were (a) all of the polysomnograms and actigrams were aligned with sleep onset, and (b) the epoch bin was only 4.8 minutes in duration. Extensive manipulation of these factors is needed to properly assess the impact that such rigid analytic parameters have on determining reliability.

Sleep architecture was reasonably reliable from night to night as evinced by the percent epoch concordance (44%). To be able to predict with approximately 50% confidence what stage a person will be in at any given time of the night (referenced to sleep onset) is reason enough for concluding that the sleep process repeats, night after night, in a uniform manner. Doubling the epoch interval might have pushed this probability to greater limits. Regardless, these results compliment the robust association evident in the global sleep parameter analysis reported above.

In comparison, body movement was less reliable, with an average correlation between nights of roughly 0.10. In retrospect, the global coefficients for BM at the right wrist were also lower than corresponding values for the sleep parameters (Table 3). Movement count, being continuous in nature, would be affected more so than sleep stages, by the rigid phase lock to sleep onset. Without the freedom to phase shift these series and perform multiple cross-correlations, even phase displacements of one epoch could return a zero correlation. Based on this argument, it is conceivable that strong relationships do exist between nights. However, low coefficients resulting from inflexible variable alignment to sleep onset could obscure these associations and mislead the researcher to conclude that they weren't there.

In general, comparable indices were evident whether intrasubject or intersubject reliability for sleep stages was considered. Most of the subjects were relatively homogenous with respect to how their sleep evolved across the night, except for the three who experienced some difficulty initiating and maintaining sleep on select occasions. These events probably accounted for their low correlations with the group as a whole. On the other hand, BM was not reliable from subject to subject on any given night. Again, the same restrictions in the model apply and more work is needed to allay this uncertainty. The epoch-by-epoch comparative method for assessing intra- and intersubject reliability is not a simple alternative to the robust global parameter approach. Conceptually, it is more complex and the results from such an analysis are easily misinterpreted. However, I believe that it has the potential to

uncover details associated with reliability in movement and sleep that could never be considered by the limited scope of the gross parameter method.

3. Movement Cycle

The principal finding of a 67.2 minute movement cycle across the night contradicts the findings of Schulz and Dirlich (1973). They reported the presence of a 100 minute cycle evident in "part of the night" (i.e., only after SWS was ended). Because the present analysis was performed on the entire night's activity, the results may not be comparable.

Before discussing these results, I must take issue with several points concerning Schulz and Dirlich's report. They restricted their analyses to the REM-nonREM phase of the overnight sleep period and as such, would have discarded approximately 100 minutes of data from each sleep record. The remaining duration of 350 minutes would have been insufficient to perform a reliable autocorrelation at the resultant 200 lags (100 min cycle). Secondly, their description of the data reduction process was too vague to invite structured criticism. They report that single night patterns were shifted in time according to a common criterion (i.e., possibly by aligning the REM periods). Derivation of their dependent measure was equally confusing. It appeared to be a rank sum of codes for different body movement types.

The clue to this apparent cycle difference, aside from the shortcomings of the Schulz and Dirlich study, may reside in the notion

that overnight sleep is the sum of two distinct sleep periods (i.e., SWS and the REM-nonREM sleep phases). Aaronson et al. (1982) describe sleep in terms of two major periods of immobility, 60 minutes in duration (SWS component) followed by recurring periods of immobility, 90 minutes apart (REM-nonREM component).

The cycle reported here may represent an amalgamation of these two phenomena or indeed, it may be describing a bonafide movement cycle waxing and waning every 70 minutes or so. One thing is certain, this cycle is reliable. Time series analysis of the individual actigrams served to verify that the 70 minute cycle is not an artifact of the data averaging process. The majority of the actigrams either revealed movement periodicities of 67.2 or 73.6 minutes which corresponds well with the cycle derived from the averaged actigram. It is also possible that the data reduction, resulting in an epoch duration of 3.2 minutes, squeezed the wave form into a faster oscillating pattern. Certainly, the reduced data epoch eliminated unnecessary resolution. However, it may have jeopardized sensitivity in the exchange.

Of all the curves fitted in this exercise, movement was the least robust ($R^2 = 0.22$). Although the information derived from the time series model was adequate for predicting periodicity, it was obvious that other factors, such as the individual sleep stages, were more important in explaining this movement-related variability.

The technique used to transform the sleep stages into time series has been reported previously (Broughton, DeKoninck, Gagnon, & Dunham, 1989; Broughton, DeKoninck, Gagnon, Dunham, & Stampi,

1990) and the polynomial sleep stage curves, though abbreviated, were very similar in form to those reported by Broughton and associates. The most interesting of these curves was that of Slow Wave sleep. The two principal phases of this stage were clearly defined with crests at roughly 30 minutes and 110 minutes after sleep onset. More intriguing was the re-emergence of this sleep state at 220 minutes and 300 minutes even though the magnitudes (% content) were significantly reduced. This unexpected persistence of SWS into the latter half of the night was traced back to a number of subjects who showed this phenomenon consistently across recordings. Unfortunately, I have had little or no success in substantiating this observation (i.e., after conversations with Oxford Medical Inc. [L. Davies, personal communication, May 1990] and other laboratories presently using this equipment [e.g., A. Sharpley, personal communication, May 1990]).

The similarities between models for the average actigram and %Stage 1 suggests that these two processes are mirror reflections of one another. Even though they each consisted of different dependent measures (i.e., movement count [transformed] and % content, respectively), the polynomial approximations revealed practically identical sweeps. The oscillation components were strikingly similar (i.e., 67.2 min and 70.4 min, respectively), as was the phase relationship (i.e., body movement lagged behind Stage 1 by 3.2 min, only). Simply interpreted, transitions into Stage 1 sleep were generally preceded by movement of some sort. This implied association substantiates the claim for a 67.2 minute movement rhythm, uncompromised by differential SWS

and REM-nonREM phases of sleep.

Not surprisingly, %Stage 2 and %REM were inverse images of one another. Although they each cycled through the same time corridor, they were visibly phase inverted. As Stage 2 would wax, REM would wane and vice versa. The slightly shortened period for REM (86.4 min vs. 90-100 min) is probably due to the fact that the initial 40 minutes of sleep was totally devoid of REM. Again, no attempt was made to "fix up" the record (i.e., selectively remove data) as a means of enhancing the presentation of this phenomenon.

The fact that time could only account for 15% of the variability in the movement index prompted the examination of its relationship to the sleep stages. The choice of the *transfer-function* methodology was quite logical. By removing (i.e., accounting for) the impact of time on each variable through time series modeling, the remaining variability, still resident in their respective residual series, was free to be assessed without bias. The extreme phase displacements between the actigram and percents REM and Stage 2 argue against any substantial associations.

Percent Wake, Stage 1, and SWS present a very different set of circumstances. Not surprisingly, %Wake and the averaged actigram were strongly positively correlated and they were in direct phase with one another (i.e., no lag or lead). Modeling the actigram with both time and %Wake would have produced a more robust fit. Unfortunately, the importance of such an exercise would have been diminished by the obvious parallelism between wakefulness and movement. Alternatively, any relationship existing between sleep-based movement and Stage 1 or

SWS would be far more interesting. The relationship between Stage 1 and BM does bring to mind the long-standing controversy over whether Stage 1 is a bonafide sleep stage or a mere extension of wakefulness. These data would argue that Stage 1 is neither sleep nor wake but a transitional state, entered into following arousal and quickly exited for a more stable sleep stage. It is worth noting that %SWS was the second most potent predictor of the actigram process; next to %Wake. Its order of importance is somewhat misleading since it could only account for 8% of the variability. Actually, all of the sleep stages, together could only explain 19% of the variability in the actigram series.

Modeling sleep stages and BMs with time series procedures was an essential exploratory exercise but it is obvious that this is only a beginning for a much needed indepth study. A comprehensive effort, uncompromised by other less related issues, would serve to resolve many of the uncertainties mentioned above and hone the finer aspects of these relationships which are evident from this first sweep of analyses. Dissociation of the SWS and REM-nonREM components is the next logical step in this analytic process. The success of such a venture hinges upon finding a valid means of splicing together identical sleep components so that adequately lengthy time series can be fashioned for a statistically valid assessment.

Sleep Parameters

1. Sleep Stages

The results of the sleep stage analysis confirm the general trend reported in the literature (Sassin & Johnson, 1968; Naitoh et al., 1973; Alihanka, 1982; Wilde-Frenz & Schulz, 1983; Pollmaecher & Schulz, 1987). Movement rates do decline substantially as sleep deepens (see **Figure 10**). The lack of a significant statistical difference between Stage 2 and SWS is paled in contrast to the actual metric difference which ranks Stage 2 as being more active. Several interrelated factors may have contributed to this apparent lack of statistical sensitivity. The issue of case weight is perhaps the most obvious. Analysis of variance was performed on mean movement rates per sleep stage and as indicated in the results section, these rates were based on grossly unequal sample bins. The natural structure of sleep offers up only a minimum percentage of time spent in Wake or Stage 1. Roughly equal time is spent in REM and SWS and approximately 50% of the night's sleep is devoted to Stage 2, alone. Random sampling within epoch bins is circumvented by the less than 10% total time spent in Wake and Stage 1. Some form of weighting or correction bias based on the stage bin variance is needed to compensate for these discrepancies.

Another probable source of statistical insensitivity is the inclusion of WASO/MT and Stage 1 in the analysis. One could argue against including these pseudo sleep stages on the basis of their distinct

Figure 10. SLEEP STAGE SCHEMATIC A modular representation of the body movement index for separate sleep stages.

antisleep characteristics. In effect, the immense movement variability inherent to these stages has circumvented past attempts to include them in any objective stage differential analysis (cf. Alihanka, 1982; Wilde-Frenz & Schulz, 1983; Pollmaecher & Schulz, 1987). Most researchers have ignored WASO/MT and Stage 1 (Sassin & Johnson, 1968; Naitoh et al., 1973) due to this overwhelming heterogeneity of variance. Achieving interstage homogeneity of variance through selective stage inclusion may be offset by the reduced within-subjects error degrees of freedom. This scenario of give and take may actually be a no-win situation.

The epoch-by-epoch stage processes illustrated in **Figure 8** are deserved of several comments. Similarities do exist between these plots and those of Pollmaecher and Schulz (1987); if only the 9th to the 21st epoches of their time series are considered. The reason for this qualifier stems from the fact that they did not separate the stage shift from the stage holding time. Although the dependent measures were quite different, the patterns were generally congruent. I would argue that the average actigraphic count per epoch (i.e., the measure used in this study) is better suited for expressing the time dependent dynamic as evinced by the dramatic swings in movement during WASO/MT and Stage 1 (cf. Pollmaecher and Schulz, 1987).

The half cycle sinusoid mapped out in the REM sleep process is intriguing. If one were to extrapolate by double plotting these data or by chaining individual REM episodes, a 5 to 6 minute rhythm would emerge, suggesting that the fine motor movements (i.e., twitches and jerks) wax and wane with a fixed periodicity. This phenomenon could also impact on

our understanding of dream mentation in some correlative or causal fashion.

The SWS plot indicates that movement increases with time spent in that stage. This agrees with the findings of Aaronson et al. (1982) and Pollmaecher and Schulz (1987) and is likely due to the impending shift back into Stage 2. Aaronson and colleagues referred to this as the ascending phase of nonREM sleep and stated that the probability of movement occurring during this time was high.

It is obvious that each sleep stage can be differentiated from any other on the basis of average rate of movement. In my view, if a sensitive enough device is used to quantify the activity (e.g., the actigraph), no ambiguity remains. Stage-specific average measures of movement and corresponding time-dependent profiles offer the promise of a more detailed sleep stage scoring system based on body movements, alone (cf. Webster et al., 1982). It is conceivable, given a broad set of parameters and an appropriate means of differentiation (e.g., polychotomous regression), that sleep stages, rather than just Sleep/Wake states, could be identified by movement.

2. Sleep Stage Shifts

The results concerning differences in movement rate for sleep stage shifts were commensurate with the literature (Muzet et al., 1972; Aaronson et al., 1982). The generalization that shifts into deeper sleep (e.g., Stage 2 to SWS) are characterized by episodes of immobility and

shifts into lighter sleep (e.g., SWS to Stage 2) are characterized by major body movements, is substantiated (see Figure 11). However, the data reveal several interesting relationships not readily encompassed by this rule. The first is the nonsignificant difference in movement rate between Stage 2 to REM and REM to Stage 2 shifts. Although gross movement rates are statistically similar for these shifts, if emphasis is placed on the actual difference (i.e., $M_{\text{St 2-REM}} = 0.49$ and $M_{\text{REM-St 2}} = 0.63$), a new pattern emerges. In simple terms, shifts out of Stage 2 involve less movement while shifts into Stage 2 involve more movement. In this model, Stage 2 becomes critical as a *fulcrum*, mediating the periodic expression of REM and facilitating descent into Slow Wave sleep.

The other nonsignificant comparison that seems incompatible with the deeper / lighter rule is between Stage 1 to Stage 2 and SWS to Stage 2. In this case, the movement rates are identical but describe descending and ascending transitions, respectively. The alternative, fulcrum hypothesis, poses no difficulty in assimilating this finding (i.e., both transitions end in Stage 2).

The time-based profiles of the stage shifts were quite distinct. The SWS and REM transitions into Stage 2 were similar in form though they differed in overall magnitude. Essentially, movement mounted progressively and eventually crested several epoches after entering the new stage. Movement rate then dropped off as precipitously as it rose. Stage 1 to Stage 2 was, unlike the other shifts to Stage 2, linear with a constant drop in movement across the duration. Some might argue that

Figure 11. STAGE SHIFT SCHEMATIC A modular representation of the body movement index for separate sleep stage shifts.

this is evidence against the fulcrum hypothesis. Transitions out of Stage 2 were generally flat although magnitude differences were apparent.

It is unfortunate that other sleep stage shifts (e.g., REM to Stage 1 and Stage 1 to SWS) could not be analyzed because they did not occur often enough or uniformly from subject to subject. Another factor influencing these results was the length and stage breakdown of the sample window. The decision to include four preshift and eight postshift epochs was made somewhat arbitrarily and this could have influenced the results dramatically. A sound iterative examination of this data reduction method is called for and could establish reliable parameters for replicating and expanding this research.

3. *Sleep/Wake Scoring*

The results of this exercise were comparable to previous studies (Mullaney et al., 1980; Webster et al., 1982) and generally improved upon them. For example, this is the first time a robust prospective test of a retrospectively developed algorithm has been reported. Mullaney and associates used no prospective sample to validate their findings and Webster et al. employed a *jack-knife* test with three subjects in one experiment and confounded their other prospective sample with patient data. With respect to the present study, both the retrospective and prospective tests of the algorithm produced astonishingly similar results; attesting to the robustness of the model.

Secondly, no measure of epoch-by-epoch agreement from the past,

has reached the current value of 96.9%. Mullaney et al. (1972) reported the closest at 96.3% and though the difference seems miniscule, it can account for a substantial number of epochs. Thirdly, the ratio of erroneous epochs for Wake misclassified Sleep is 2 : 1, whereas Mullaney and colleagues found their best ratio was 3 : 1.

In agreement with past efforts, the real weakness in movement-based Sleep/Wake prediction is evident when the participant is awake, as determined by his or her polysomnogram, but is lying very still. In agreement with Webster et al. (1982), the preponderance of movement epochs misclassified Sleep were found in the sleep onset period; not in the sleep period. Note that this claim is based on percent differences which were determined so that the comparatively short duration of the sleep onset period was equated with the longer sleep period.

The logistically-derived algorithm reported here is quite interesting from several angles. Recall that the equations developed in Kripke's laboratory (see pp 16-17 of this document) were lengthy and complex (i.e., incorporating some 8 to 10 variables and a constant). On the other hand, the heuristic devised and implemented by Newman et al. (1988) was simple, nonmathematical and just as effective for scoring Sleep and Wake. The equation derived in this study corroborates and mathematically substantiates this simpler method. For example, the stepwise inclusion of lagged and led epochs abruptly terminated after the designated movement epoch, and the epoch following that - were introduced. Basically, this regression produced a moving window, 64 seconds in duration, beginning with the designate epoch. Newman et

al. employed a 60 second moving window (three 20 s epoches) and similarly, it began with the designate epoch. Both methods improved prediction by examining the movement over the next 30 to 40 seconds after the actual event of interest. Incorporating information from beyond this boundary, either before or after the event, did not improve the odds of predicting the Sleep/Wake state.

It is important to note that several assumptions concerning the regression were violated. The first was the assumption of independence between observations. Clearly, the time series nature of this data, with its certain positive autocorrelation or memory, is incongruent with this axiom. It would not be unreasonable to model the series with a Box-Jenkins analysis and thus, eliminate this source of covariance. Conditional upon a Durbin-Watson statistic of roughly 2.0, the memory-free residual time series could then be substituted for the original data, before processing. Secondly, the distribution of sleep states was heavily skewed (*assumption of normality*) in favour of Sleep (i.e., Wake accounted for only 6.4% of the observations). This drawback could be easily overcome by extending the recordings into the waking phase of the 24 hour day; effectively loading the sample with Wake epoches.

Aside from the purely practical applications suggested by this research (e.g., an automated Sleep/Wake scoring system), a number of salient spin-offs deserve mention. First, if the use of stepwise logistic regression has been successful in discriminating Sleep and Wake states, perhaps the more complex algorithms associated with polychotomous regression will serve to distinguish the actual sleep stages from one

another as a function of BM index. This is not an unreasonable assumption when one considers the sleep stage and stage shift results reported earlier. Work along these lines is currently underway.

Another course of study suggested by this research is the development of a catalogue of algorithms that would take into consideration a number of factors including epoch length, limb differences, and state of health. For example, it would be useful to know if this algorithm is as effective in predicting *state* when the epoch length is doubled to 64 seconds or halved to 16 seconds. Should the algorithm not be flexible enough to compensate for this change, new epoch-specific replacements would need to be generated.

Another issue that has not received enough attention in this study is the Side by Limb interaction reported earlier. Unfortunately, we know very little about how the right wrist behaves in conjunction with the other three sites even though the data was collected. A detailed analysis, specifically oriented towards exploring the relationships between the principal sites of movement could begin to address unilateral and bilateral versus global movement differences. In addition, the protocol could be improved with the incorporation of telemetry-based kinesthetic sensors placed at key points on the body where movement is probable. In conjunction with the actigraphs, these sensors can relay data to a computer-generated graphic image of the sleeping subject. This image mirrors the movements which can be stored for future reference and study.

Finally, the flexibility of this algorithm must be tested for clinical

applications. Narcoleptic-cataplectics, hypersomniacs, sleep apneics, sleep maintenance insomniacs, etc., may require algorithms unique to their pathologies. Certainly, sleep-based movement disorders such as PLMS and fragmentary myoclonus; and the movement-based parasomnias such as sleep walking and REM behavior disorder, would present enormous challenges to the prediction of Sleep/Wake states by actigraphy.

Conclusions

The basis for this research is primarily technical in origin. It does not extend from nor operate within a theoretical framework for why we move in our sleep. No attempt has been made to explain the results in light of theory because theories have not received sufficient attention to warrant serious consideration (cf. Gardner & Grossman, 1975). Several proposals stemming from the animal literature do show promise and could conceivably provide the necessary background from which to formulate and test hypotheses.

Gardner and Grossman (1975) discuss the evidence in light of two theories, the afferent or "discomfort" theory and the efferent or central activation theory. The basic premise underlying the afferent theory is that gross movements occur to relieve afferent pain stimuli consequent to immobility. Supporters of this theory argue that movement actually preserves sleep by ensuring its continuation. Experiments involving

exteroceptive manipulation of the sleeping subject have been cited as evidence in favor of this argument. The efferent theory postulates that central activation or arousal in the brain (e.g., *K-complexes*) triggers the global body movements. Studies showing night-to-night reliability and sleep stage – stage shift relationships with movement are offered in support of this position. Unfortunately, experiments have not yet reached the sophistication required to dissociate these two phenomena. At best, the efferent and afferent theories of movement origin need not be irreconcilable. It can be argued that movements and central activation are inextricably linked in a positive feedback loop that progresses across the night (i.e., the *crescendo effect*). Beginning at an arbitrary point, movement triggers neural activation which drives the motor system to initiate movement, which in turn, triggers neural activation, and so on.

Immobility may reflect some fundamental process of the brain during sleep, which simultaneously and similarly deactivates both the cerebral cortex and the motor apparatus. Based on animal models, the lack of gross motor movement in REM sleep is due to an active inhibition at the postsynaptic (spinal) membranes of the motor neurons (Chase et al., 1980). In contrast, the immobility present in SWS appears to be due to motor cortex disfacilitation (Evarts, 1964). Control *gates* at the cerebral and spinal levels suggest a bimodal switching mechanism for turning off movement. The probability of movement occurring is greatest during the switch between the disfacilitatory (nonREM) and inhibitory (REM) modes of control. This model argues for a short delay between deactivation of one locus and activation of the other. It is during this

delay (i.e., 1 to 3 min) that control is temporarily lost and movement bursts are unleashed. This theory is cursory at best; however, it does introduce several enlightening and flexible concepts that may be molded and shaped into a cogent explanation for why we move during sleep.

In anticipation of just such a research objective, the actigraphs were programmed to collect data in 2 second epoches and great care was taken to ensure precise synchronization between all of the recording devices. A micro-analysis of the PSG and actigraphic data collected in the present study could begin to address some of the postulates comprising this theory.

In conclusion, the actigraph has proven to be a welcome addition to a unique group of apparatus designed and engineered for the purpose of ambulant physiological research. It is simple to use and its versatility is bounded only by the limits of the researcher's ingenuity. Of all the different mechanisms and devices used to study BMs in both sleep and wake, it is the least disruptive and noninvasive. Nevertheless, it does have its drawbacks. For example, it provides an incomplete reflection of the actual muscle activity. Large movements restricted to the monitored limb may be easily misconstrued as global postural shifts involving the entire body. Other limitations include too little memory, too short a battery-life expectancy, and general defects at the manufacturing level which result in periodic equipment failure. All limitations aside, the actigraph makes it possible to record quantifiable aspects of a subject's sleep behavior in the comfort of the home, rather than the sleep laboratory. With a device of

comfort of the home, rather than the sleep laboratory. With a device of this calibre, the behavioral scope of sleep research could be expanded to include, not only limb-to-limb relationships, but person-to-person, behavior-to-behavior, and species-to-species interactions. This technique may open the way to an *ethology* of human sleep behavior that could provide new insights into the behavioral, functional, and clinical significance of the sleep cycle.

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APPENDICES

APPENDIX A

EDINBURGH HANDEDNESS INVENTORY

Name: _____

Date of Birth: _____ Sex: _____

PLEASE READ THESE INSTRUCTIONS CAREFULLY BEFORE STARTING.

Please indicate your preference in the use of hands in the following activities by putting + in the appropriate column.

Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, put + +.

If in any case you are really indifferent as to which hand to use, put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all, of the object or task.

	LEFT	RIGHT
1. Writing	_____	_____
2. Drawing	_____	_____
3. Throwing	_____	_____
4. Scissors	_____	_____
5. Toothbrush	_____	_____
6. Comb	_____	_____
7. Hammer	_____	_____
8. Screwdriver	_____	_____
9. Knife (without fork)	_____	_____
10. Spoon	_____	_____
11. Push Broom (upper hand)	_____	_____
12. Striking Match (match)	_____	_____
13. Opening Box (lid)	_____	_____
i Which foot do you prefer to kick with?	_____	_____
ii Which eye do you use when using only one?	_____	_____

PLEASE DO NOT WRITE IN THIS SPACE

L.Q. (WD) = _____

L.Q. (O) = _____

L.Q. (SL) = _____

APPENDIX B

SLEEP HISTORY (confidential)

A. PERSONAL DATA:

Name: _____
 Address: _____
 Phone no.: _____
 Age: _____ Sex: _____ Preferred hand _____
 Occupation: _____ Shift(s): _____

B. SLEEP HABITS:

What time do you usually go to bed on weekdays? _____
 weekends? _____

What time do you usually get up on weekdays? _____
 weekends? _____

On average, how long does it take you to fall asleep after you turn out the lights? _____

On average, how long do you actually sleep at night? _____

Do you awaken during the night? yes _____ no _____ If so, approximately how often? _____ How long do these periods of arousal last? _____

Are you refreshed when you awaken in the morning? yes _____ no _____

Do you nap during the daytime? yes _____ no _____ If so, how often and how long are the naps? _____

Do you find yourself falling asleep when you don't mean to? yes _____ no _____

If so, do you dream during such an episode? yes _____ no _____

Are you bothered by sleepiness during the day? yes _____ no _____

Have you ever experienced doing something without being aware at the time of the action? yes _____ no _____

Have you ever suddenly fallen? yes _____ no _____

Have you ever experienced sudden body weakness? yes _____ no _____

Have you ever experienced weakness or paralysis upon going to sleep or on awakening from sleep? yes _____ no _____

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Have you ever hallucinated as you are falling asleep or as you are waking up? yes ___ no ___

Do you have difficulty breathing at night? yes ___ no ___

Have you been told that you snore while asleep? yes ___ no ___

Have you ever experienced: (a) a restlessness of legs; (b) "nervous legs"; (c) a creeping sensation in your legs ; or (d) twitching prior to sleep onset or immediately upon awakening from sleep? yes ___ no ___

(If you responded yes, please circle the relevant sensation)

Has anyone ever told you that your arms or legs jerk or twitch while you are apparently asleep? yes ___ no ___

Are you aware or has anyone ever told you that you:

a) talk while apparently asleep? yes ___ no ___

b) walk while apparently asleep? yes ___ no ___

c) grit your teeth while apparently asleep? yes ___ no ___

d) wet the bed during sleep? yes ___ no ___

e) were a bed wetter between the ages of 8 and 14? yes ___ no ___

f) have disturbing dreams? yes ___ no ___

Are you satisfied with the quality of your sleep in general? yes ___ no ___

If not, please list complaints or make comments: _____

Are you taking sleep medication? yes ___ no ___ If so, for what purpose? _____

Please specify type and frequency of use _____

C. FAMILY HISTORY:

Has anyone in your family been known to have any sleep problems? yes ___ no ___

If so, please list type of problem(s) and relationship of this person to you _____

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D. PHYSICAL HEALTH STATUS:

Do you have a medical condition (e.g., diabetes, epilepsy, kidney/liver dysfunction, menopause, pregnancy, etc.)? yes ____ no ____ If so, please specify _____

Are you currently taking any medication (prescribed or otherwise)? yes ____ no ____

If so, please specify _____

On average, how many cups of coffee and/or tea do you drink each day? _____

On average, how many cigarettes, cigars or pipefuls of tobacco do you smoke daily? _____

On average, how many alcoholic beverages do you drink on weekdays? _____
weekends? _____

Do you smoke marijuana or use illegal drugs? yes ____ no ____

If so, please list and give approximate use per week _____

Thank you for completing this questionnaire

APPENDIX C

HÔPITAL GÉNÉRAL D'OTTAWA
OTTAWA GENERAL HOSPITAL
300 CHENEE STREET EAST OTTAWA K1H 8L2

CONSENTEMENT À DES RECHERCHES MÉDICALES
CONSENT FOR MEDICAL RESEARCH

Nom de l'étude-Name of research project

Chercheur-Researcher

Je consens à la participation de.

I consent to the participation of

(patient)

(patient)

à l'étude précitée et j'autorise par la présente le(s) médecin(s) et chercheur(s) à procéder aux examens et/ou à dispenser les traitements suivants.

in the above study and hereby authorize the physician(s) and investigator(s) to proceed with the following examinations and/or to administer these treatments.

J'ai reçu une explication détaillée de tous les effets secondaires et des risques connus ayant trait aux examens et aux traitements

I have had a detailed description of all the known side effects and risks related to the examinations and treatments

J'ai également reçu une description de tous les avantages à attendre de ces examens et de ces traitements. On m'a fait connaître d'autres formes d'examen et de traitements

I have also received a description of any benefits that may be expected from these examinations and treatments. Alternative forms of examinations and treatments have been disclosed to me

J'ai eu l'occasion de poser des questions au sujet de ces examens et de ces traitements et on y a bien répondu

I have been given an opportunity to ask questions concerning the examinations and treatments involved and the questions which I have asked have been adequately answered

On m'a dit que je pouvais retirer mon consentement et suspendre ma participation à l'étude à n'importe quel moment et pour quelque motif que ce soit.

I have been told that I can withdraw my consent and stop my participation in the study at any time and for any reason

En toute connaissance de cause, je consens volontairement à participer à cette étude

With full knowledge of this, I voluntarily consent to participate in the study

PATIENT OU PERSONNE LÉGALEMENT RESPONSABLE PATIENT OR PERSON LEGALLY RESPONSIBLE

1. WITNESS _____
Name _____ Signature _____ Date _____

2. WITNESS _____
Name _____ Signature _____ Date _____

APPENDIX D

a) *Data Estimation:*

As reported in the results section, five cases of apparent equipment malfunction were detected during the course of the study. Although the trains of anomalous data were relatively short (less than 1 hour), they tended to occur in actigraphs worn on the left wrist (four of five). The overall effect, though minimal, would undoubtedly elevate the movement index artificially at the left wrist. Unfortunately, the analysis of variance supported this finding, effectively rendering any conclusions uninterpretable due to the potential confound.

Three proofing schemes were devised and tested back to back, in an effort to correct for this circumstance and substantiate the actual effect. The first attempt involved the conservative practice of discarding all data from the affected subjects. Four of the 11 subjects were dropped from the analysis and the remaining sample was analyzed with a completely within-subjects $3 \times 2 \times 2$ (Night by Side by Limb) ANOVA (see Table D1). The results, though lacking power, were similar to those of the confounded analysis with one exception; the right ankle moved more than the left ankle (see Table D2 and D3).

The second scheme was less stringent, but also involved the sacrifice of "good" data as a consequence of removing "bad" data. Essentially, the actual trains of erroneous movement counts were excised from the five affected actigrams. Epoch-matched sections from the three

Table D1

Analysis of variance of total accumulated body movement per night comparing wrists and ankles on the left and right sides of the body between three consecutive weeknights of sleep (n = 7).

<i>Source of Variance</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>
A (Nights)	683.84	2	341.92	2.22
A(error)	1851.36	12	154.28	
B (Side)	3.94	1	3.94	1.69
B(error)	14.01	6	2.34	
C (Limb)	37.58	1	37.58	2.87
C(error)	78.64	6	13.11	
AxB	0.31	2	0.16	0.10
[AB](error)	19.07	12	1.59	
AxC	0.64	2	0.32	0.25
[AC](error)	15.57	12	1.30	
BxC ^a	64.01	1	64.01	19.17*
[BC](error)	20.04	6	3.34	
AxBxC	0.95	2	0.47	0.87
[ABC](error)	6.56	12	0.55	

Note. To facilitate comprehension, the sums of squares and mean squares are multiplied by the constant, 10^{-5} .

^a Simple main effects analysis of the Side by Limb interaction is presented in Table D2.

* $p < .01$

Table D2

Simple main effects analysis of variance of total accumulated body movement per night for the Side by Limb interaction (n = 7).

<i>Source of Variance</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>
<u>B (Side) at C (Limb)</u>				
B at c ₁ (wrist)	18.10	1	18.10	7.25*
B at c ₁ (error)	14.98	6	2.50	
B at c ₂ (ankle)	49.85	1	49.85	15.68**
B at c ₂ (error)	19.08	6	3.18	
<u>C (Limb) at B (Side)</u>				
C at b ₁ (left)	99.84	1	99.84	8.22*
C at b ₁ (error)	72.87	6	12.15	
C at b ₂ (right)	1.75	1	1.75	0.41
C at b ₂ (error)	25.81	6	4.30	

Note. To facilitate comprehension, the sums of squares and mean squares are multiplied by the constant, 10^{-5} .

Means are presented in Table D3.

* $p < .05$

** $p < .01$

Table D3

Mean total accumulated body movement per night for the Side by Limb interaction (n = 7)

Side	Limb			
	Wrist		Ankle	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Left	4084.1 ^a	2946.0	3108.9	2580.8
Right	3668.9	2812.2	3798.8	2992.5
^a n = 21 observations.				

corresponding actigrams were also clipped out. The results were almost identical to the *small n* analysis (i.e., the ankles were not significantly different) and the original *confound* analysis.

The third approach involved replacing the five corrupted values with predictions, generated by a *maximum likelihood estimation* statistic (Dixon et al., 1990). This iterative routine (BMDP5V) is designed for use with unbalanced repeated measures models and, based upon estimated regression and covariance parameters, it provides best guess replacement values for missing data. The size of the matrix, number of missing values, and proximity of the missing values to each other within the matrix are factors that influence the accuracy of the predictions. In this case, only 5 of 132 data points were missing, and though the left wrist was most affected, these values were distributed evenly across nights.

Again the results (Table 1a, 1b, 1c) were congruent with the overall finding of a significant elevation of movement in the left wrist as compared to the other three sites. The estimation method was preferred over the others, for a number of reasons. This technique was free of any conscious data manipulation such as selective removal of raw data or subjects from the overall analysis. Unlike the estimation procedure, the other methods resulted in the elimination of valid data; an undesirable side effect of discarding corrupted values. This practice is difficult to reconcile under any circumstances. Finally, the justification for estimating data is more easily defended when the heuristic is grounded in documented mathematical logic.

Because these peculiar trains of elevated BM counts were relatively

unique to the actigraphs worn on the left wrist, the second most active site; the right wrist ($M = 4249.4$), was chosen as the source of body movement data for all remaining analyses. Careful examination of these actigrams revealed no indication of any equipment malfunction.

b) *Natural Logarithmic Transformation:*

The magnitude of the standard deviations in relation to the means in Table 1c indicate that movement is extremely variable across the night. This becomes more evident when the same counts are sorted by sleep stage. Wakefulness after sleep onset and Stage 1 are characteristic of a very broad range of movement counts while movement profiles in the other sleep stages have much smaller standard deviations. This variance inequality seriously hampered statistical comparisons between sleep stages and between stage shifts. Transformation was considered over the nonparametric alternative as a means of preserving the inherent parametric nature of the data. A number of recommended conversions were assessed (Kirk, 1982) including the square root and the base 10 logarithm but a natural logarithmic transformation ($\ln [x + 1]$) was chosen. It was very effective in reducing the variability associated with WASO and Stage 1 while exerting a minimal influence on Stage 2, REM, and Slow Wave sleep.

It has recently come to my attention that Ambulant Monitoring Inc. has redesigned the actigraph digital processor to collect data in a similar, nonlinear fashion (R. Cole, personal communication, November 1990).

APPENDIX E

Table E*Box-Jenkins time series analysis of body movement index for individual actigrams*

Subject/Night	Model	Period (min)	Mean Square error	Durbin Watson statistic
M.W./N1	(1,0,1)(1,0,1)	73.6	1.65	2.00
M.W./N2	(2,0,0)(1,0,0)	60.8	1.54	1.96
M.W./N3	(1,0,1)(1,0,0)	73.6	1.53	1.93
K.C./N1	(1,0,1)(1,0,0)	64.0	1.15	1.99
K.C./N2	(0,0,0)(1,0,0)	96.0	1.20	1.67
K.C./N3	(0,0,1)(1,0,0)	60.8	1.17	2.04
J.G./N1	(1,0,0)(1,0,0)	89.6	1.74	2.01
J.G./N2	(1,0,0)(0,0,1)	89.6	1.72	2.04
J.G./N3	(1,0,0)		1.82	2.07
A.W./N1	(0,0,0)(0,0,1)	67.2	1.87	1.95
A.W./N2	(2,0,0)(1,0,0)	57.6	1.49	2.03
A.W./N3	(1,0,0)(0,0,1)	67.2	1.66	2.09
W.D./N1	(1,0,0)		1.70	2.02
W.D./N2	(1,0,0)(0,0,1)	89.6	1.69	2.10
W.D./N3	(1,0,0)(0,0,1)	86.4	1.65	2.00
L.M./N1	(0,0,1)		1.68	1.99
L.M./N2	(0,0,0)(0,0,1)	67.2	1.73	2.05
L.M./N3	(0,0,0)(0,0,1)	76.8	1.79	1.97

Note. Epoch duration is 3.2 min.

Table E (continued)*Box-Jenkins time series analysis of body movement index for individual actigrams*

Subject/Night	Model	Period (min)	Mean Square error	Durbin Watson statistic
A.P./N1	(1,0,1)(0,0,1)	73.6	1.65	1.80
A.P./N2	(0,0,0)(0,0,1)	64.0	1.72	1.97
A.P./N3	(1,0,1)(1,0,1)	67.2	1.63	1.98
J.N./N1	(0,0,1)(1,0,0)	64.0	1.62	1.98
J.N./N2	(1,0,0)(0,0,1)	73.6	1.58	1.97
J.N./N3	(0,0,1)		1.62	1.97
C.G./N1	(2,0,2)(0,0,1)	73.6	1.64	1.98
C.G./N2	(1,0,1)(1,0,0)	70.4	1.80	2.00
C.G./N3	(1,0,1)(0,0,1)	60.8	1.79	1.99
L.S./N1	(0,0,0)(0,0,1)	70.4	1.79	1.84
L.S./N2	(2,0,0)(0,0,1)	89.6	1.93	2.00
L.S./N3	(0,0,0)(1,0,0)	99.2	1.85	1.85
J.M./N1	(1,0,0)(0,0,1)	73.6	1.54	2.01
J.M./N2	(0,0,1)(0,0,1)	67.2	1.60	2.02
J.M./N3	(1,0,1)		1.73	2.02

Note. Epoch duration is 3.2 min.

Figure E. MOVEMENT CYCLE. Frequency distribution of significant periods of movement for individual actigrams.

END

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FIN